

# Winter and spring evolution of northern seasonal deposits on Mars from OMEGA on Mars Express

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[1] The OMEGA visible/near-infrared imaging spectrometer on Mars Express has observed the retreat of the northern seasonal deposits during Martian year 27–28 from the period of maximum extension, close to the northern winter solstice, to the end of the retreat at  $L_s$  95°. We present the temporal and spatial distributions of both CO<sub>2</sub> and H<sub>2</sub>O ices and propose a scenario that describes the winter and spring evolution of the northern seasonal deposits. During winter, the CO<sub>2</sub>-rich condensates are initially transparent and could be in slab form. A water ice annulus surrounds the sublimating CO<sub>2</sub> ice, extending over 6° of latitude at  $L_s$  320°, decreasing to 2° at  $L_s$  350°, and gradually increasing to 4.5° at  $L_s$  50°. This annulus first consists of thin frost as observed by the Viking Lander 2 and is then overlaid by H<sub>2</sub>O grains trapped in the CO<sub>2</sub>-rich ice layer and released during CO<sub>2</sub> sublimation. By  $L_s$  50°, H<sub>2</sub>O ice spectrally dominates most of the deposits. In order to hide the still several tens of centimeters thick CO<sub>2</sub> ice layer in central areas of the cap we propose the buildup of an optically thick top layer of H<sub>2</sub>O ice from ice grains previously embedded in the CO<sub>2</sub> ice and by cold trapping of water vapor from the sublimating water ice annulus. The CO<sub>2</sub> ice signature locally reappears between  $L_s$  50° and 70°. What emerges from our observations is a very active surface-atmosphere water cycle. These data provide additional constraints to the general circulation models simulating the Martian climate.

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## 1. Introduction

[2] The formation and sublimation of seasonal deposits on the surface of Mars are major elements controlling its atmospheric circulation and its climate. Asymmetric cyclic seasonal variations of the surface pressure of up to ~30% have been measured by Viking landers [Tillman *et al.*, 1993]. Global circulation models have shown that these changes in total atmospheric mass are induced by a complex competition between sublimation of CO<sub>2</sub> frost from one hemisphere, interhemispheric transport and recondensation at the surface of the opposite polar regions [Hourdin *et al.*, 1993; Forget *et al.*, 1998].

[3] Ground-based observations of the seasonal deposits have been limited to retreat phases as caps are tilted away

from the Sun and Earth during the formation phases. Terrestrial observations of the receding northern seasonal deposits have been obtained during aphelic oppositions when Mars is relatively small in diameter, and even then the poles were near the limb, thus preventing a reliable analysis of the range of phenomena encountered and their variability. Antoniadi [1930] and Fischbacher *et al.* [1969] summarized many of these early terrestrial observations and Cantor *et al.* [1998] reported on the Hubble Space Telescope (HST) observations of several north polar retreats.

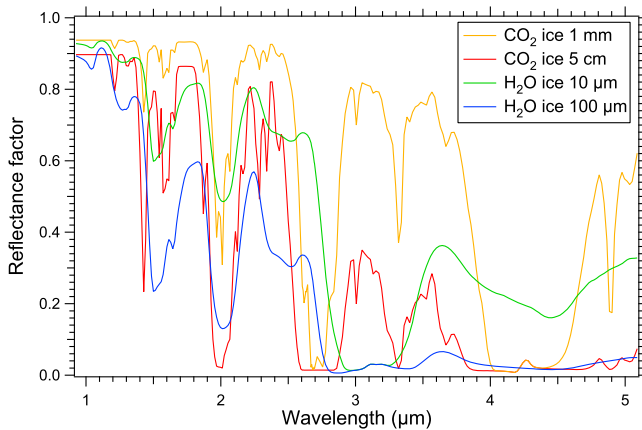
[4] Spacecraft orbiting Mars have documented the evolution of the northern seasonal deposits with much higher spatial resolution. Mariner 9 acquired three synoptic views of the northern seasonal deposits in mid-late spring of Martian year 10 [Soderblom *et al.*, 1973] and Viking orbiters also monitored the spring retreat of the deposits in Martian years 12 and 13 [James, 1979, 1982] (Martian years (MY) defined by Clancy *et al.* [2000] began with MY 1 starting at the 1955 vernal equinox,  $L_s = 0^\circ$ , where  $L_s$  is the aerocentric longitude of the Sun). However, the orbits of Viking spacecraft were not favorable for synoptic observations of the seasonal deposits since the resolution near Viking periapsis was too high to allow monitoring more than a small longitude. Mars Orbiter Camera (MOC) and Thermal Emission Spectrometer

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**Figure 1.** Spectra of CO<sub>2</sub> ice with grain sizes of 1 mm (orange) and 5 cm (red) and H<sub>2</sub>O ice with grain sizes of 10 μm (green) and 100 μm (blue) modeled using a radiative transfer code developed by *Douté and Schmitt* [1998] and optical constants of H<sub>2</sub>O ice [*Grundy and Schmitt*, 1998; *Schmitt et al.*, 1998] and CO<sub>2</sub> ice [*Quirico and Schmitt*, 1997; *Schmitt et al.*, 1998].

(TES) instruments aboard the Mars Global Surveyor (MGS) spacecraft monitored four complete spring retreats of the northern seasonal deposits between 1999 and 2006 (MYs 25 to 28) [*James and Cantor*, 2001; *Benson and James*, 2005; *Kieffer and Titus*, 2001]. More recently, the Mars Reconnaissance Orbiter Mars Color Imager (MARCI) instrument aboard Mars Reconnaissance Orbiter (MRO) recorded the MY 29 spring retreat [*Cantor et al.*, 2010].

[5] Near-infrared spectrometry [*Herr and Pimentel*, 1969; *Larson and Fink*, 1972; *Calvin and Martin*, 1994] and observations in the thermal infrared [*Neugebauer et al.*, 1971; *Kieffer*, 1979; *Kieffer et al.*, 2000] demonstrated that CO<sub>2</sub> ice is the major component of the seasonal deposits. It was previously proposed that there might be an annulus of water ice just south of the receding CO<sub>2</sub> ice condensates [*Houben et al.*, 1997]. The similarity in reflectance between CO<sub>2</sub> and H<sub>2</sub>O ices makes the distinction difficult in the visible range. Thermal infrared observations may partially resolve the composition of the ices since regions covered by CO<sub>2</sub> frost have a temperature <150 K due to the thermodynamic equilibrium with the atmosphere. Brightness temperatures in the 160 to 180 K range provide evidence for H<sub>2</sub>O frost coverage, but such intermediate temperatures can also result from spatial mixing of CO<sub>2</sub> ice-covered and ice-free regions within field of view (FOV). The TES spectrometer on board MGS observed such a relatively warm and bright ring lagging a few degrees of latitude behind the receding boundary of regions at CO<sub>2</sub> sublimation temperature, interpreted as H<sub>2</sub>O frost [*Kieffer and Titus*, 2001]. *Wagstaff et al.* [2008] processed data from Thermal Emission Imaging System (THEMIS) spectrometer to monitor the spatial distribution of this moderately cold annulus during northern spring. However, *Kieffer and Titus* [2001] already pointed out that an unambiguous identification of ices in seasonal deposits required investigations in the near-IR (1 to 5 μm), as both H<sub>2</sub>O ice and CO<sub>2</sub> ice present strong diagnostic absorption bands in this spectral range.

[6] The OMEGA imaging spectrometer aboard Mars Express covers a spectral range from 0.36 μm to 5.09 μm, extending from the visible across the near infrared, with a spectral resolution varying from 14 to 23 nm. The instantaneous field of view of OMEGA varies from less than 300 m at periapsis to several kilometers depending on the position of the Mars Express spacecraft on its elliptical orbit [*Bibring et al.*, 2004]. Strong distinct signatures of H<sub>2</sub>O ice and CO<sub>2</sub> ice (Figure 1) with major absorption bands at 1.25, 1.5, 2, and 3 μm (H<sub>2</sub>O ice) and 1.435, 2.281, 2.7, and 3.3 μm (CO<sub>2</sub> ice) [*Grundy and Schmitt*, 1998; *Quirico and Schmitt*, 1997; *Hansen*, 2005] are measured throughout images at different resolution. Therefore, the OMEGA instrument has the capability of unambiguously identifying and monitoring the abundance, physical state, distribution and temporal evolution of the CO<sub>2</sub>, H<sub>2</sub>O and dust components of the Martian frosts and ices. For instance, the composition of the seasonal deposits can be determined precisely, i.e., CO<sub>2</sub> ice with minor inclusions of water ice and dust [*Schmitt et al.*, 2005] and the presence of a CO<sub>2</sub>-free water ice annulus lagging a few degrees behind the receding CO<sub>2</sub>-rich condensates is confirmed [*Bibring et al.*, 2005]. This information is of prime importance for the understanding of the microphysics and the thermodynamics (radiative equilibrium) of the sublimation/condensation/deposition processes of volatiles. The TES instrument has shown that a large amount of water is released in the atmosphere during northern spring while CO<sub>2</sub> frost is sublimating, then continuing during part of the summer season [*Smith*, 2004; *Pankine et al.*, 2010]. An important question is the identification of the water vapor sources (seasonal deposits, permanent cap, regolith, etc.) as well as their relative contributions. The spatial distribution and absolute abundance of the deposits and their seasonal evolution provides strong constraints on the seasonal cycle of volatile exchange (mainly sublimation/condensation fluxes of CO<sub>2</sub> and H<sub>2</sub>O) between the surface and the atmosphere. The abundance of dust within CO<sub>2</sub> or H<sub>2</sub>O ices should also constrain the codeposition processes occurring during fall and winter. All of these data should also provide some clues to understand the current and past climatic cycles through the study of interannual evolutions.

[7] The organization of this paper is as follows. In section 2 we describe the OMEGA observations used in this study and the spectral parameters selected to monitor the seasonal deposits. Then in section 3 we present maps of the spatial distribution of both CO<sub>2</sub> and H<sub>2</sub>O ices until complete disappearance of CO<sub>2</sub> ice. We analyze the boundaries of the seasonal deposits in terms of albedo, CO<sub>2</sub> ice, and H<sub>2</sub>O ice, comparing OMEGA observations with MOC, TES, and THEMIS results. We also propose an interpretation for the early disappearance of the CO<sub>2</sub> ice spectral signature. Finally, in section 4 we present a possible scenario depicting the winter and spring evolution of the northern seasonal deposits and discuss the implications of these results.

## 2. OMEGA Observations and Relevant Parameters

### 2.1. OMEGA Observations

[8] Since January 2004, the OMEGA instrument has monitored three complete retreats of the northern seasonal

deposits. The present contribution is focused on the 2006 retreat, corresponding to MY 27 winter and MY 28 spring. The 2006 retreat will be called MY 27–28 retreat in the rest of the article. Northern seasonal deposits monitored during previous Martian years began receding near  $L_s$  320° [Kieffer and Titus, 2001]. The OMEGA instrument has observed the seasonal deposits as soon as  $L_s$  280°, just after winter solstice. These early observations correspond to the maximum extent of the seasonal deposits. We selected observations until  $L_s$  95°, just after the summer solstice. After  $L_s$  95°, seasonal frost is confined on the north permanent cap and disappears during summer [Langevin et al., 2007]. A large number (1060) of OMEGA observations with adequate S/N ratio have been selected to follow the MY 27–28 retreat of the northern seasonal deposits.

## 2.2. Relevant Spectral Parameters for Seasonal Deposits Monitoring

### 2.2.1. Reflectance at 1.08 $\mu\text{m}$

[9] The seasonal deposits were first detected on the basis of their high albedo. MOC, TES and MARCI instruments monitored the albedo of the deposits from MY 24 to 29 [James and Cantor, 2001; Benson and James, 2005; Kieffer and Titus, 2001; Cantor et al., 2010]. It is therefore important to monitor the albedo so as to compare the MY 27–28 OMEGA observations with previous observations. The albedo retrieved from MOC, TES, and MARCI measurements corresponds to a reflectance factor (RF), i.e., the ratio of the observed radiance to the incoming solar flux per unit of surface:

$$\text{RF}(\lambda) = \frac{I(\lambda)}{F_{\text{Sun}}(\lambda) \cos(\theta_i)}$$

where  $I(\lambda)$  is the radiance measured by the sensor,  $F_{\text{Sun}}(\lambda)$  is the solar flux at the top of the atmosphere, and  $\theta_i$  is the incident zenith angle. This reflectance factor was monitored in a 575–625 nm band pass by MOC [James and Cantor, 2001], by a visible/near IR bolometer (0.3 to 2.9  $\mu\text{m}$ ) on TES [Kieffer and Titus, 2001; Christensen et al., 2001] and in seven bands centered between 258 nm and 718 nm by MARCI [Cantor et al., 2010]. The OMEGA spectral range extending from 0.36  $\mu\text{m}$  to 5.09  $\mu\text{m}$  is covered by a visible channel and two IR channels [Bibring et al., 2004]. We monitored the albedo in the low-wavelength IR channel instead of the visible channel for two reasons: the visible channel spatial resolution is lower than the IR channels spatial resolution and aerosol scattering decreases with increasing wavelength. The spectel at 1.08  $\mu\text{m}$  located in the continuum was chosen. This spectel was used by Langevin et al. [2007] for its high S/N ratio to study the evolution of the southern seasonal deposits. The reflectance of pure ices is expected to have high albedo for small-grained frost across the visible and near IR. Therefore, the main differences observed between albedo at  $\sim 0.6$   $\mu\text{m}$  (MOC) and 1.08  $\mu\text{m}$  (OMEGA) should result from the larger aerosol contributions in the visible. Relative variations of albedo with time as observed by OMEGA, MOC, TES, and MARCI can directly be compared.

[10] The reflectance factor does not depend on lighting and observing geometries for a perfect Lambertian surface.

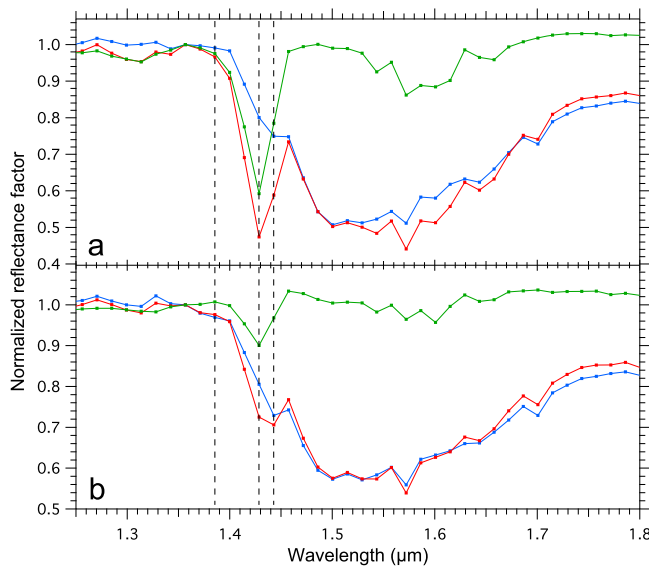
However, ices and snow do not behave as Lambertian reflectors [Li et al., 2007; Warren, 1982; Dumont et al., 2010]. Specular reflection can occur for slab ices. The albedo of snow, i.e., hemispherical reflectance, increases with incidence angle. A strong forward scattering peak is another non-Lambertian effect observed for terrestrial snow [Dumont et al., 2010]. If reflectance factor variations are observed in the OMEGA data set, it is therefore important to distinguish between photometric effects and changes induced by surface modification. Furthermore, aerosol extinction and scattering can have a significant effect on albedo as northern polar regions are observed at high incidence angles. In particular, albedo of bright surfaces such as ices is moderated by aerosols and spectral contrast is lowered [Vincendon et al., 2007]. The impact of aerosols and photometric effects is discussed in section 2.2.4.

### 2.2.2. CO<sub>2</sub> Ice

[11] CO<sub>2</sub> ice is the main component of both northern and southern seasonal deposits. Several CO<sub>2</sub> ice absorption bands are available in the OMEGA spectral range (Figure 1). The narrow 1.435  $\mu\text{m}$  absorption band provides the best S/N ratio among the CO<sub>2</sub> ice bands which do not saturate, except for path lengths greater than 20 cm. Therefore this absorption band was used by Langevin et al. [2007] to study the evolution of the southern seasonal deposits. We use this same band to probe CO<sub>2</sub> ice. This absorption band lies very close to a minor absorption feature of atmospheric CO<sub>2</sub>, at 1.443  $\mu\text{m}$ . It is also overlapped by the short-wavelength wing of the broad 1.5  $\mu\text{m}$  absorption feature of H<sub>2</sub>O ice which extends from 1.38  $\mu\text{m}$  to 1.8  $\mu\text{m}$  (Figure 1). Langevin et al. [2007] used the spectel at 1.429  $\mu\text{m}$ , the closest to the bottom of this band and near the optimum of the photometric function of OMEGA. They developed a specific CO<sub>2</sub> band depth evaluator for the OMEGA data so as to minimize the impact of these absorption features:

$$R_{\text{CO}_2} = \frac{\text{RF}(1.429 \mu\text{m})}{\text{RF}(1.385 \mu\text{m})^{0.5} \times \text{RF}(1.443 \mu\text{m})^{0.5}}$$

The baseline spectel at 1.385  $\mu\text{m}$  is located outside the wide 1.5  $\mu\text{m}$  absorption band of H<sub>2</sub>O ice while the baseline spectel at 1.443  $\mu\text{m}$  lies within the short-wavelength wing of this H<sub>2</sub>O ice absorption band.  $R_{\text{CO}_2}$  is a reflectance ratio,  $(1 - R_{\text{CO}_2})$  is then dimensionally equivalent to a band strength.  $(1 - R_{\text{CO}_2})$  is very close to 0 for modeled and observed spectra of pure H<sub>2</sub>O ice so that large admixtures of H<sub>2</sub>O frost have only a small impact on this evaluator. Since the baseline spectel at 1.443  $\mu\text{m}$  is located within the H<sub>2</sub>O ice absorption band,  $(1 - R_{\text{CO}_2})$  underestimates the strength of the CO<sub>2</sub> ice band. We evaluate the band strength by comparing spectra of two regions located at similar altitudes, so as to have the same absorption by atmospheric CO<sub>2</sub> at 1.443  $\mu\text{m}$ . In the first region, spectra exhibit both CO<sub>2</sub> and H<sub>2</sub>O signatures. In the second region, spectra have been chosen to exhibit the same H<sub>2</sub>O ice band strength at 1.5  $\mu\text{m}$  as in the first region but without CO<sub>2</sub> ice signature (Figure 2). We assume that the mixing of atmospheric and ices signature is multiplicative. By dividing these two spectra, we delete the effect of both the H<sub>2</sub>O ice band and the 1.443  $\mu\text{m}$  atmospheric band. We thus obtain an undisturbed band



**Figure 2.** Evaluation of the CO<sub>2</sub> ice band strength at 1.429  $\mu\text{m}$ . (a) Red spectrum taken on a region covered by CO<sub>2</sub> ice including low content of H<sub>2</sub>O ice and (b) red spectrum taken on a region covered by CO<sub>2</sub> ice including a relatively high content of H<sub>2</sub>O ice. The red spectra exhibit both CO<sub>2</sub> and H<sub>2</sub>O ice absorption bands, whereas the blue spectra exhibit no CO<sub>2</sub> ice signatures but the same H<sub>2</sub>O ice band strength at 1.500  $\mu\text{m}$  as in the red spectra. Red and blue spectra are taken in regions located roughly at the same altitude so as to have the same absorption by atmospheric CO<sub>2</sub> at 1.443  $\mu\text{m}$ . Both spectra are normalized to the reflectance value at 1.357  $\mu\text{m}$ . Green spectra are obtained by dividing the red spectrum by the corresponding blue spectrum. They provide an estimate of the CO<sub>2</sub> ice band strength at 1.429  $\mu\text{m}$ : 0.408 for the region of Figure 2a and 0.120 for the region of Figure 2b. These estimates are very consistent with the values provided by the  $\text{BD}_{\text{CO}_2}(1.429 \mu\text{m})$  evaluator when applied on the red spectra: 0.410 for Figure 2a and 0.110 for Figure 2b. Dashed lines indicate the position of spectels used for this evaluation.

strength of the CO<sub>2</sub> ice at 1.429  $\mu\text{m}$ . We did this work for 8 different CO<sub>2</sub> ice band strengths. We also evaluated the mean value of  $(1 - R_{\text{CO}_2})$  for regions not covered by CO<sub>2</sub> ice but still exhibiting the 1.5  $\mu\text{m}$  H<sub>2</sub>O ice absorption band. An analysis of spectra and latitudinal profiles of both  $(1 - R_{\text{CO}_2})$  and the H<sub>2</sub>O ice signature has been done at several steps of the seasonal deposits retreat. It indicates that for the vast majority of observations no CO<sub>2</sub> ice signature is observed for H<sub>2</sub>O ice signature at 1.5  $\mu\text{m}$  lower than 0.15.  $(1 - R_{\text{CO}_2})$  takes small fluctuating values on defrosted regions, probably because of varying surface dust spectra or modification of the optical depth of atmospheric dust. These values are not relevant; only  $(1 - R_{\text{CO}_2})$  values where the H<sub>2</sub>O ice signature is higher than 0.05 are considered. We therefore defined the CO<sub>2</sub> zero level as the average of  $(1 - R_{\text{CO}_2})$  on regions where the H<sub>2</sub>O ice signature ranges from 0.05 to 0.15. The correlation between the undisturbed band strengths and the corresponding values of  $(1 - R_{\text{CO}_2})$

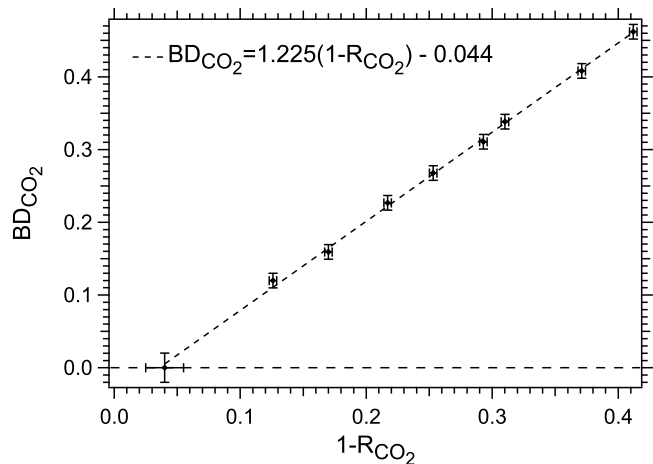
led to the following evaluator for the strength of the CO<sub>2</sub> ice band at 1.429  $\mu\text{m}$  (see Figure 3) (BD, band depth):

$$\text{BD}_{\text{CO}_2}(1.429 \mu\text{m}) = 1.225(1 - R_{\text{CO}_2}) - 0.044$$

We estimate the uncertainty on the determination of this band depth to  $\pm 0.01$  reflectance unit.

### 2.2.3. H<sub>2</sub>O ice

[12] The presence of area of H<sub>2</sub>O ice in the northern seasonal deposits has been inferred by TES temperature measurements [Kieffer and Titus, 2001] on the basis of its temperature intermediate between that of CO<sub>2</sub> ice (150 K) and defrosted dust (>220 K). It was then directly detected by the OMEGA instrument [Schmitt *et al.*, 2005]. H<sub>2</sub>O ice has several broad absorption bands in the OMEGA spectral range. The strongest bands are located at wavelengths of 1.5  $\mu\text{m}$ , 2  $\mu\text{m}$  and 3  $\mu\text{m}$  (Figure 1). The 3  $\mu\text{m}$  absorption band saturates when the path length of photons within H<sub>2</sub>O ice exceeds a few  $\mu\text{m}$ . Longer paths are required for the 2  $\mu\text{m}$  band (a few hundred  $\mu\text{m}$ ) and the 1.5  $\mu\text{m}$  band ( $\sim 1$  mm) [Grundy and Schmitt, 1998]. The grain sizes for H<sub>2</sub>O ice on the surface ranges between a few tens of  $\mu\text{m}$  (frost) and about 1 mm (perennial northern ice cap) [Langevin *et al.*, 2005]. Therefore the 3  $\mu\text{m}$  band is not best suited to monitor the texture of surface ice, while it is a sensitive indicator for minerals hydration [Jouglet *et al.*, 2007; Milliken *et al.*, 2007; Pommerol and Schmitt, 2008a, 2008b]. At wavelengths around 2  $\mu\text{m}$ , there are strong CO<sub>2</sub> absorption features both in the solid state (Figure 1) and in the atmosphere. Therefore the 1.5  $\mu\text{m}$  band is clearly best suited to monitor H<sub>2</sub>O ice on the surface with OMEGA. This spectral range provides optimum S/N [Langevin *et al.*, 2007]. It saturates only for very large grain sizes which are not expected for surface frost, and there are only weak CO<sub>2</sub> absorptions from either ice or gas at the center of the band (Figure 1). We used the evaluator developed by Langevin *et al.* [2007]. They compared the reflectance factor at 1.5  $\mu\text{m}$  to a continuum evaluated from the reflectance factor at two OMEGA wavelengths 1.385  $\mu\text{m}$  and 1.772  $\mu\text{m}$  away from major CO<sub>2</sub> and H<sub>2</sub>O absorption bands, taking into account the intervals



**Figure 3.** Correlation between the undisturbed band strengths  $\text{BD}_{\text{CO}_2}(1.429 \mu\text{m})$  and the corresponding values of  $(1 - R_{\text{CO}_2})$ .



between the center of the band and the selected continuum regions:

$$BD_{H_2O}(1.500 \mu m) = 1 - \frac{RF(1.500 \mu m)}{RF(1.385 \mu m)^{0.7} \times RF(1.772 \mu m)^{0.3}}$$

We estimate the uncertainty on the determination of this band depth to  $\pm 0.005$  reflectance unit.

[13] An instrumental problem was identified in the observation mode of OMEGA with the largest swath (128 pixels), with one out of two lines being perturbed for columns 81 to 96 after orbit 511. This problem extended to columns 65 to 128 after orbit 2124. In these parts of the image cubes, the corrupted observations were replaced by the average of the uncorrupted previous and next lines. However, the correction on spectels used in both the CO<sub>2</sub> and H<sub>2</sub>O ice absorption strength evaluators is not fully reliable. Therefore, while still containing interesting information for mapping purposes (in particular for the albedo at 1.08  $\mu m$ ), the last 64 columns of 128 columns mode images have to be considered with caution and they cannot be used for spectral modeling purposes.

#### 2.2.4. Impact of Aerosols and Ice Photometric Effects on Reflectance and Band Strengths

[14] Northern polar regions can only be observed at relatively high incidence angles, particularly close to spring equinox with incidence angles higher than 80°. Aerosol extinction and scattering are a major factor for such geometries, even at low optical thickness conditions. Moreover, the large latitudinal extension of the seasonal deposits at the beginning of spring results in incidence angle variations of more than 30°. It is therefore important to assess the impact of atmospheric dust on the observed albedo and ices band depths before concluding on a surface modification. In order to estimate this impact, we studied the influence of illumination geometry for a 13 km<sup>2</sup> homogeneous region located on Rupes Tenuis. We selected two successive observations of this area acquired in nadir pointing mode at two different incidence angles, 60.1° and 68.6°. The region is covered by bright seasonal frost at the time of observations ( $L_s \sim 67^\circ$ ). We observe a 12% decrease of the reflectance factor at 1.08  $\mu m$  and a 12% decrease of the H<sub>2</sub>O ice band depth at 1.5  $\mu m$  when incidence angle increases, i.e., when solar photons encounter a higher quantity of aerosols. The variation of the CO<sub>2</sub> ice band depth at 1.43  $\mu m$  is within uncertainty on band depth determination. As expected, aerosol extinction and scattering lower the albedo of this bright region and reduce the spectral contrast [Vincendon *et al.*, 2007].

[15] Correcting the aerosol impact for the entire data set is not straightforward. As discussed by Vincendon *et al.* [2007], it can only be performed on regions which are observed at close intervals with two different geometries. Even then, it relies on the assumption that there is no variation of both the aerosol optical thickness and the surface between the observations. If there is only one geometry of observation available, the optical thickness of aerosols can still be determined provided some CO<sub>2</sub> ice bands show saturation such as the ones at 2.01 or 2.64  $\mu m$ . Such a method has been applied for observations of the southern seasonal deposits [Langevin *et al.*, 2007] but it is not applicable for the northern

seasonal deposits where no saturated CO<sub>2</sub> ice band are observed. We decided, as a first step, to present the time sequences of mosaics without correction of aerosol effects. The overall self-consistency of the mosaics at overlaps between swaths at different incidence angles demonstrates that this approach provides a sound basis for studying the winter and spring retreat of the northern seasonal deposits.

[16] Ice reflectance and band depths can also depend on the emission angle due to a combination between photometric effects of the ice and aerosol scattering. Most of OMEGA observations used in this study are obtained with nadir pointing. For a single 128 columns image, the emission angle varies from 0° to 10°, with only a minor impact of non-Lambertian behavior and aerosols. Nevertheless, some observations were acquired in inertial mode between  $L_s$  350° and  $L_s$  66°. In this mode, the emission angle varies from 0° to 90°. The part of the image where emission angle is higher than 55° is undersampled and entails problems of projection. For such off-nadir observations, we therefore only considered pixels for which the emission angle is lower than 55°. In order to assess the impact of non-Lambertian behavior and aerosols for emission angles lower than 55°, we studied a 13 km<sup>2</sup> homogeneous region located on Olympia Planitia. We selected two successive observations of this area acquired with an incidence angle of  $\sim 65^\circ$  at two different emission angles, 0.7° and 45.1°. The azimuth angle of the second observation is 106°. Bright seasonal frost covers the region at the time of observations ( $L_s \sim 51^\circ$ ). We observe a 14% increase of the reflectance factor at 1.08  $\mu m$  and a 9% decrease of the H<sub>2</sub>O ice band depth at 1.5  $\mu m$  when emission angle increases. The variation of the CO<sub>2</sub> ice band depth at 1.43  $\mu m$  is within uncertainty on band depth determination. It is known that the phase function of Martian aerosols is strongly forward scattering [Ockert-Bell *et al.*, 1997]. Since the azimuth of the off-nadir observation is higher than 90°, the reflectance increase observed for increasing emission angle could therefore be explained by the increase of the path radiance of the aerosols. However, surface ice also behaves as a non-Lambertian reflector with a strong forward scattering peak [Dumont *et al.*, 2010]. The reflectance increase is thus likely due to a combination of both aerosols and ice photometric effects. Interestingly, Cantor *et al.* [2010] observe similar reflectance increase for increasing emission angles while monitoring a region of the residual north polar cap in summer ( $L_s \sim 134^\circ$ ). They mention that the ranges of incidence and phase angles during these observations are very small; we can deduce that the azimuth of their off-nadir observations is close to 90°, thus comparable to the 106° azimuth of our off-nadir observation. For similar geometry of observation, Cantor *et al.* [2010] therefore observe similar reflectance variations in spite of the different nature of the ice covering the permanent cap (CO<sub>2</sub> ice in spring, H<sub>2</sub>O ice in summer) and a different aerosol optical depth.

[17] In the literature, a Henyey-Greenstein phase function with an asymmetry parameter of 0.63 is commonly chosen for aerosols [Ockert-Bell *et al.*, 1997]. On the contrary, the seasonal frost phase function is unknown. If the optical depth of aerosols was known, then the phase function of the frost could be retrieved. But the lack of saturated CO<sub>2</sub> ice band and the restricted geometries of observation prevent the determination of the aerosol opacity. Therefore, it is not

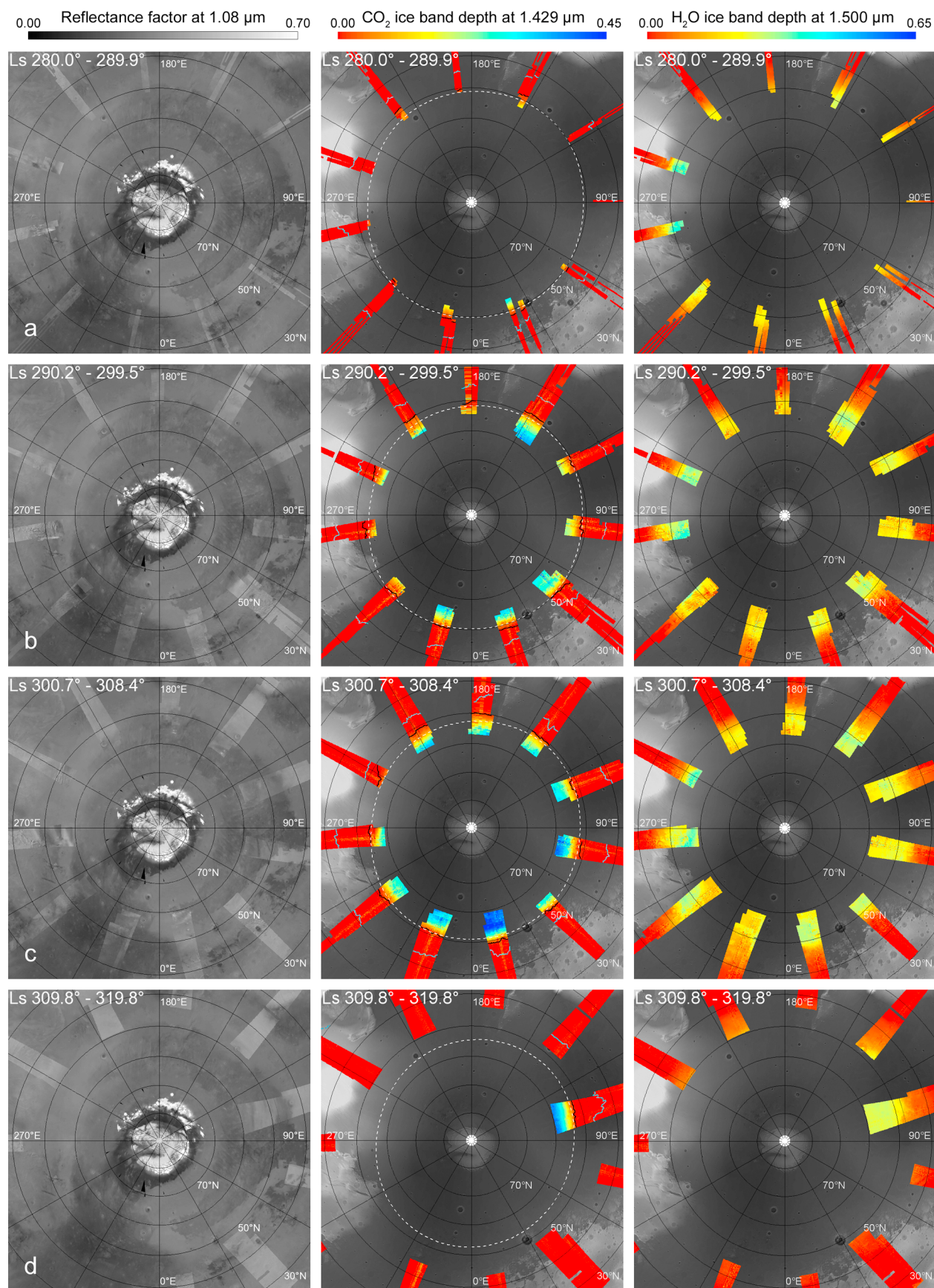


Figure 4

possible at this stage of the analysis to separate aerosols and surface effects for high emission angles. Most of the geometries of observation are generally not so extreme. As previously explained, the overall self-consistency of the mosaics demonstrates that reflectance and band depths variations are primarily due to surface modification. However, every time a significant variation of these spectral parameters is observed, we checked whether it is correlated with changes in lighting or observing geometries before concluding on a surface effect.

### 3. Temporal Evolution of the Spatial Distribution of CO<sub>2</sub> and H<sub>2</sub>O Ices

[18] The three selected evaluators (reflectance factor at 1.08  $\mu\text{m}$ , CO<sub>2</sub> ice absorption strength at 1.429  $\mu\text{m}$ , H<sub>2</sub>O ice absorption strength at 1.5  $\mu\text{m}$ ) have been calculated for the whole OMEGA data set between  $L_s$  280° and 95° and above 30°N latitude and then mosaiced into north polar stereographic projection to create temporal maps spanning 0.4 to 10°  $L_s$  depending on the density of observations. These maps are presented in Figures 4–9. Three boundaries have been added on these mosaics: the TES “crocus line” [Kieffer and Titus, 2001], the OMEGA CO<sub>2</sub> ice boundary and the OMEGA H<sub>2</sub>O ice boundary. Procedures used to retrieve these boundaries are described below.

[19] It is important to note that an ice absorption band depth is related to the total quantity of ice present on the surface only if that ice is optically thin at the band wavelength. If ice is optically thick, the band depth will strongly depend on the way the ices and dust are mixed at the pixel scale, and it will be correlated to the relative proportion between each constituent of a granular mixture, but it is also dependent on the mean ice grain size. Thus the band depth maps mostly provide a qualitative information on the repartition of both CO<sub>2</sub> and H<sub>2</sub>O ices but, in most cases, neither on the depth nor on the total amount of ice covering the Martian soil. In the rest of this paper, CO<sub>2</sub> and H<sub>2</sub>O ice absorption band depth maps will be simply called CO<sub>2</sub> and H<sub>2</sub>O ice maps. Maps of the reflectance factor at 1.08  $\mu\text{m}$  will be called albedo maps.

#### 3.1. General Description of the Maps

[20] Sections 3.1.1–3.1.3 give a general description of the northern seasonal deposits evolution in term of albedo, CO<sub>2</sub> ice coverage, and H<sub>2</sub>O ice coverage.

##### 3.1.1. Albedo Maps

[21] From  $L_s$  280° to  $L_s$  340° (Figures 4a to 5b), seasonal deposits are seen on both CO<sub>2</sub> and H<sub>2</sub>O ice maps but not on albedo maps. For a single OMEGA observation, no albedo contrast is observed at the transition between bare defrosted soil and soil covered by frost. This surprising configuration

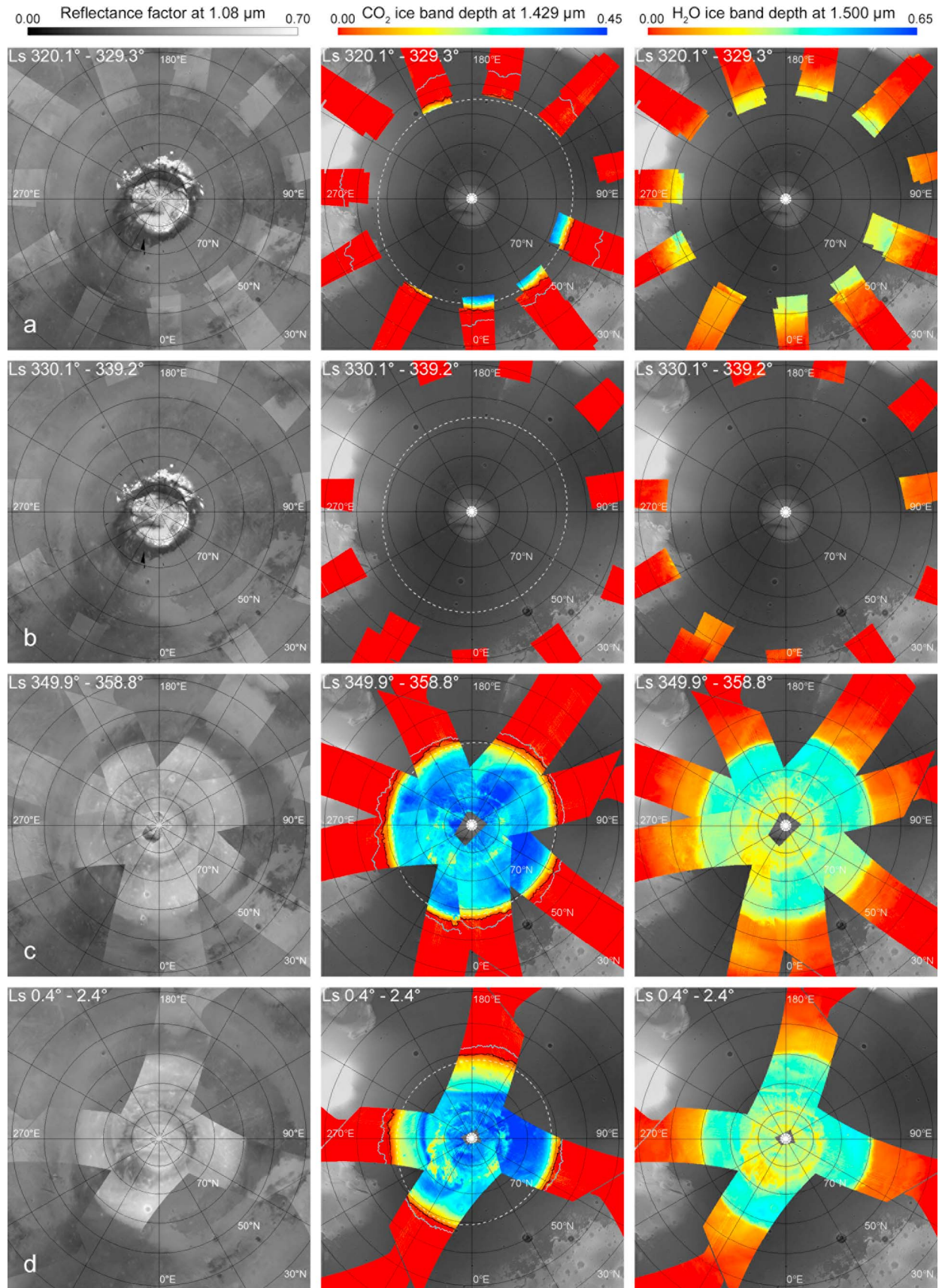
is shown on Figure 10. The distribution of the CO<sub>2</sub> ice band depth is shown on Figure 10a. Regions located north of 50°N are covered by CO<sub>2</sub>-rich ice while southern regions are not. No albedo transition is observed between these two regions on Figure 10b. Furthermore, known albedo features observed in summer on the Vastitas Borealis plains showing sharp transition between bright and dark soil are still observed in winter even on regions covered by frost. Figure 10c corresponds to MOC albedo data acquired in summer, taken from the MOC wide-angle image atlas [Caplinger and Malin, 2001]. An albedo transition is observed at ~54°N. This albedo transition is still observed in winter even with a frost coverage (Figure 10b). These characteristics tend to prove that winter northern frost is either transparent at 1  $\mu\text{m}$  or spatially segregated at subpixel scale with bare defrosted soil. If ice is spatially segregated with defrosted soil, then we would expect that more and more surface is covered by ice with increasing latitude. Then for a soil with a given summer albedo, the winter albedo should increase with latitude. It is not observed on Figure 10b on regions north 55°N. Therefore the most likely explanation is that winter frost is transparent at 1  $\mu\text{m}$ . One can argue that the two data sets are not comparable since this MOC albedo mosaic is made with the reflectance factor at 600 nm whereas OMEGA mosaics are done at 1  $\mu\text{m}$ . Therefore we also retrieved the 603 nm reflectance factor mosaics from the OMEGA visible channel observations. Comparison between the OMEGA mosaics acquired at 603 nm and at 1  $\mu\text{m}$  shows that for both mosaics no albedo contrast is observed at the transition between bare defrosted soil and soil covered by frost. The comparison between MOC and OMEGA mosaics is thus valid.

[22] Transparent frost is observed until  $L_s$  329°. Between  $L_s$  329° and  $L_s$  349°, regions covered by CO<sub>2</sub> ice have not been monitored by the OMEGA instrument. On the next OMEGA observation, at  $L_s$  350°, all the surface covered by CO<sub>2</sub>-rich seasonal frost appears brighter than bare defrosted soil (Figure 5c). This demonstrates that a change in the optical properties of the CO<sub>2</sub> frost has occurred between  $L_s$  329° and  $L_s$  350°. A MOC mosaic acquired during MY 24 at  $L_s$  343° clearly shows an albedo transition between surface covered by frost and defrosted soil [see James and Cantor, 2001, Figure 1a]. The frost physical state modification therefore occurs between  $L_s$  329° and  $L_s$  343° assuming no interannual variability between MY 24 and MY 27, an assumption supported by multiyear observations [e.g., Titus, 2009].

[23] From  $L_s$  350° to  $L_s$  95°, the seasonal deposits evolution in term of albedo is mostly the same as that observed by James and Cantor [2001], Kieffer and Titus [2001], and Benson and James [2005] in 2000 and 2002. At first glance,

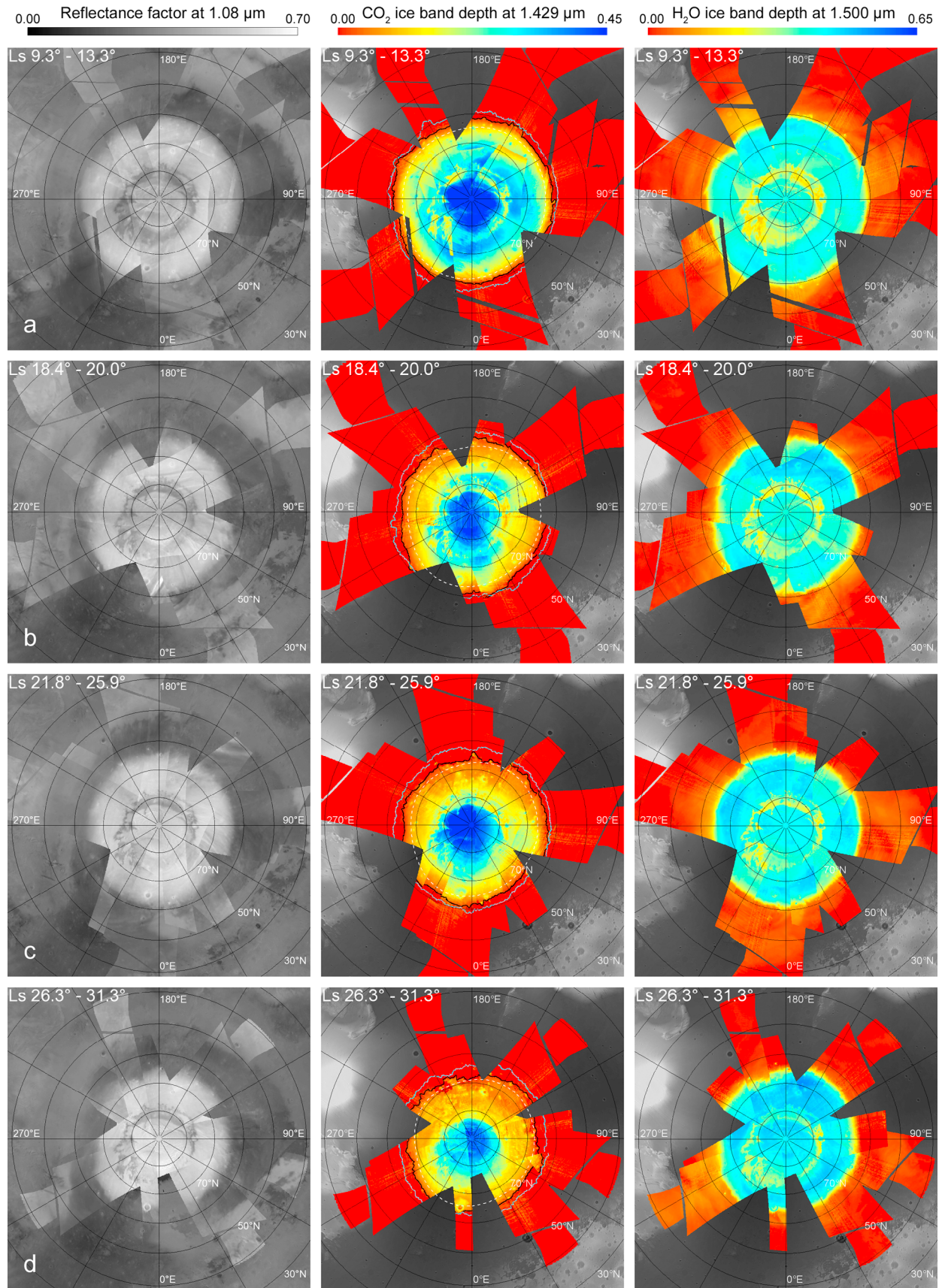
**Figure 4.** Evolution of the northern seasonal deposits in terms of (left) reflectance factor at 1.08  $\mu\text{m}$ , (middle) CO<sub>2</sub> ice band depth at 1.429  $\mu\text{m}$ , and (right) H<sub>2</sub>O ice band depth at 1.500  $\mu\text{m}$  for four sets of observations: (a)  $L_s$  280.0°–289.9°, (b)  $L_s$  290.2°–299.5°, (c)  $L_s$  300.7°–308.4°, (d)  $L_s$  309.8°–319.8°. The OMEGA albedo maps are displayed over MOC albedo data acquired in summer [Caplinger and Malin, 2001] as a background. CO<sub>2</sub> ice and H<sub>2</sub>O ice maps are displayed over MOLA topography as a background, with altitudes stretching between –5500 m and 3500 m [Zuber et al., 1998]. Three important boundaries are plotted on the CO<sub>2</sub> ice band depth map: the black outline corresponds to the OMEGA CO<sub>2</sub> ice boundary, the blue outline is the OMEGA H<sub>2</sub>O ice boundary and the white dashed outline is the TES “crocus line” (limit of low temperatures compatible with surface CO<sub>2</sub> ice, averaged over 3 MY of TES observations) computed for the mean  $L_s$  of each  $L_s$  range.





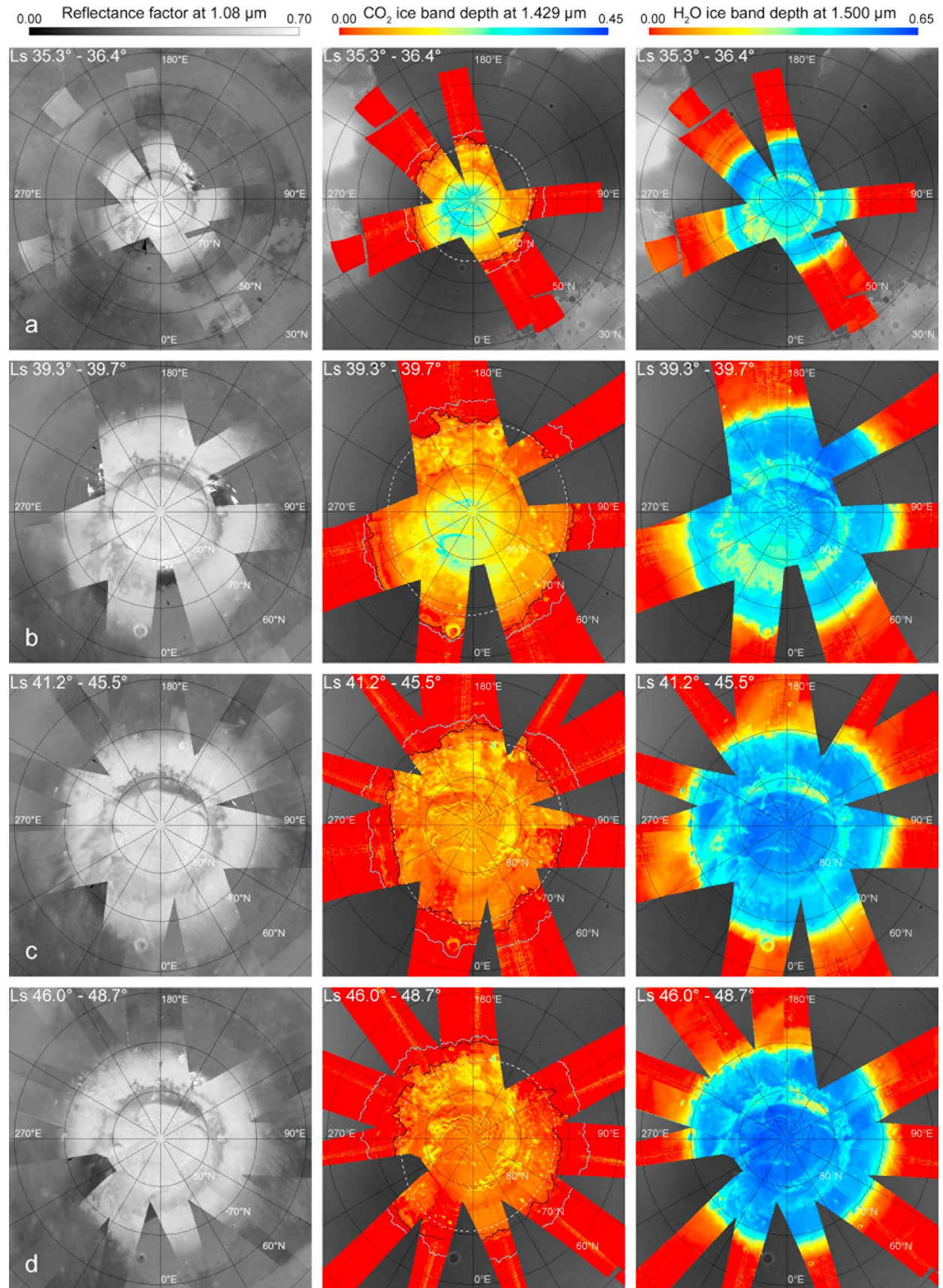
**Figure 5.** Same as Figure 4 but for (a)  $L_s$  320.1°–329.3°, (b)  $L_s$  330.1°–339.2°, (c)  $L_s$  349.9°–358.8°, (d)  $L_s$  0.4°–2.4°.





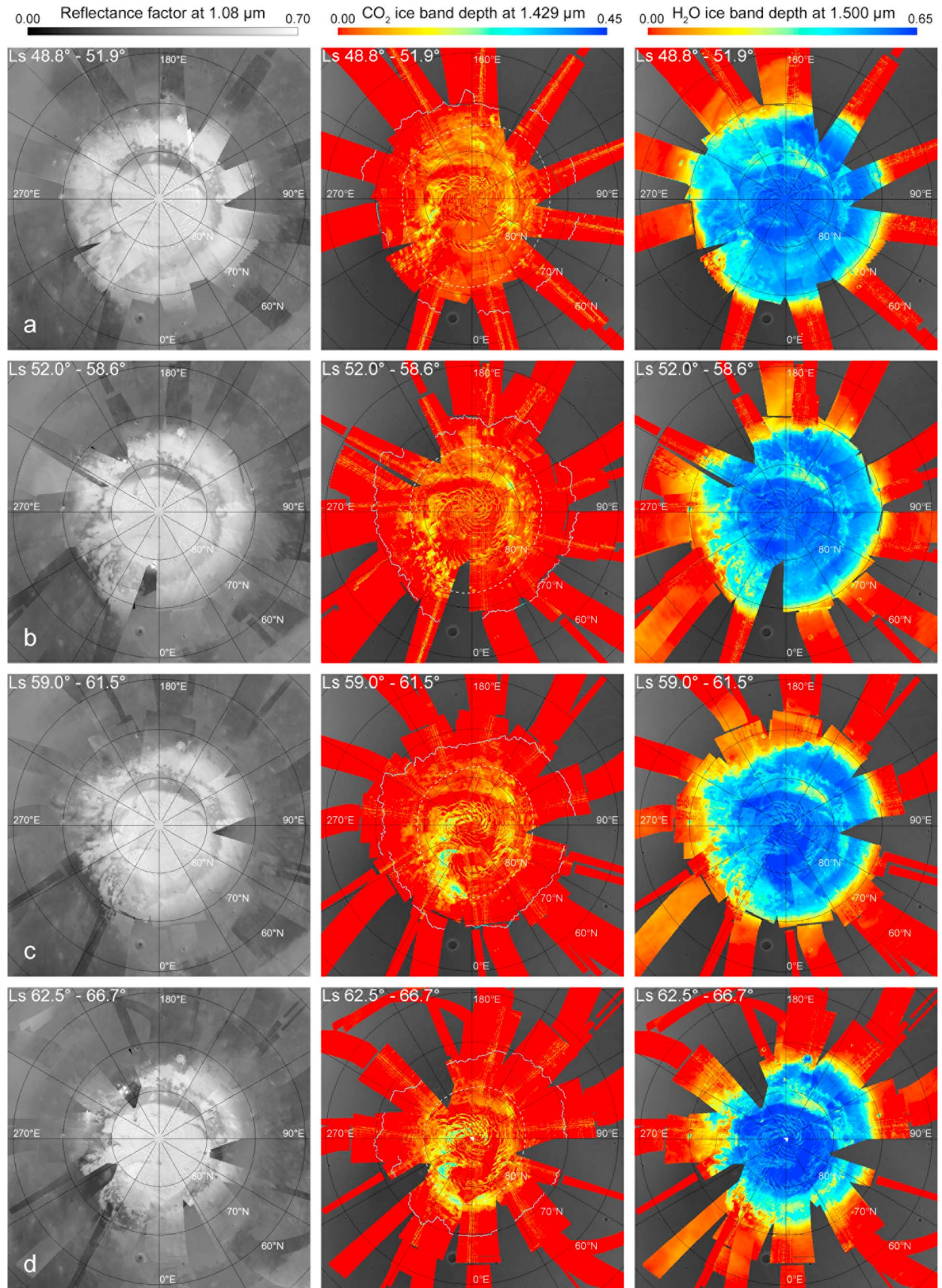
**Figure 6.** Same as Figure 4 but for (a)  $L_s$  9.3°–13.3°, (b)  $L_s$  18.4°–20.0°, (c)  $L_s$  21.8°–25.9°, (d)  $L_s$  26.3°–31.3°.





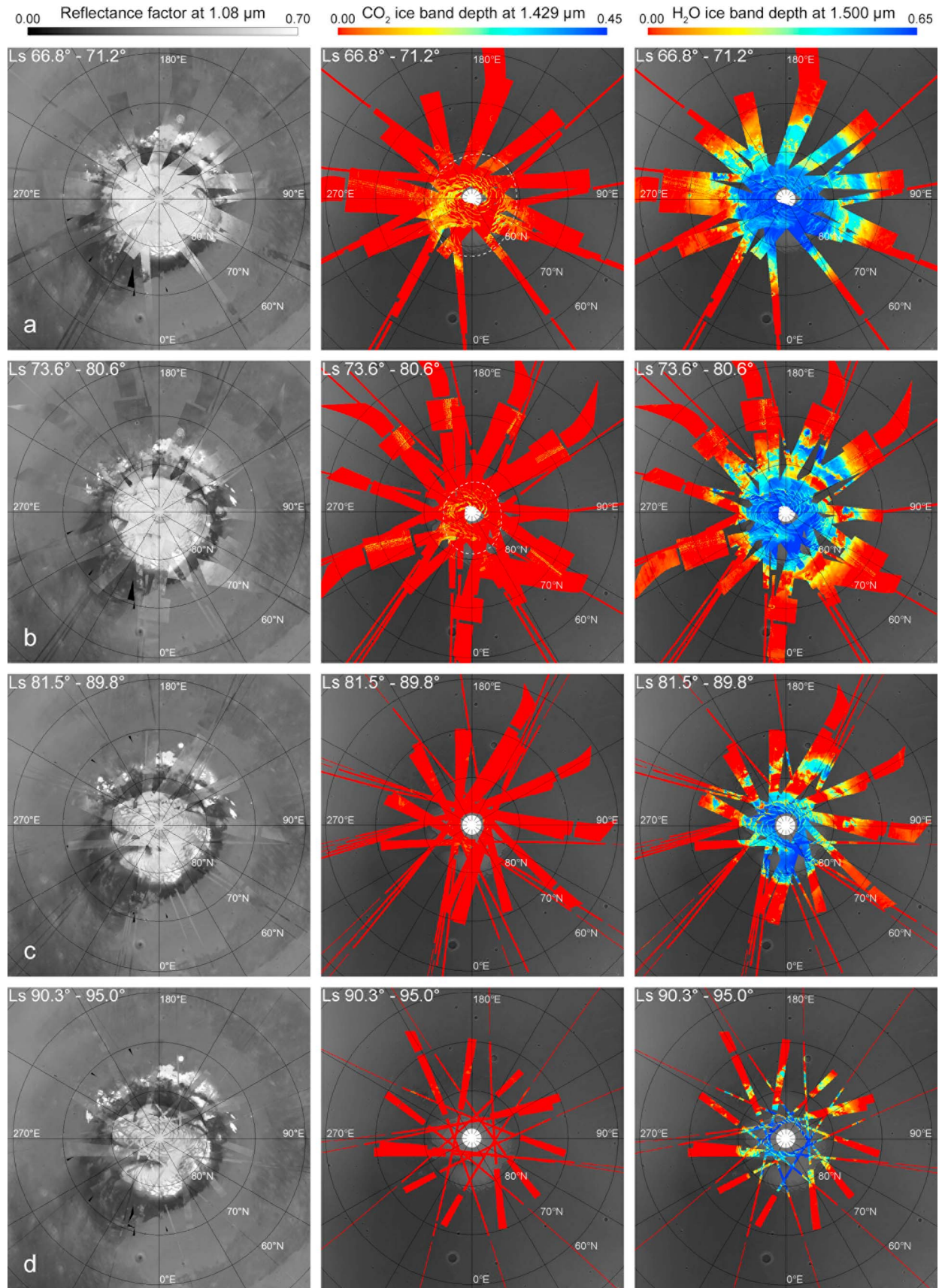
**Figure 7.** Same as Figure 4 but for (a)  $L_s$  35.3°–36.4°, (b)  $L_s$  39.3°–39.7°, (c)  $L_s$  41.2°–45.5°, (d)  $L_s$  46.0°–48.7°.





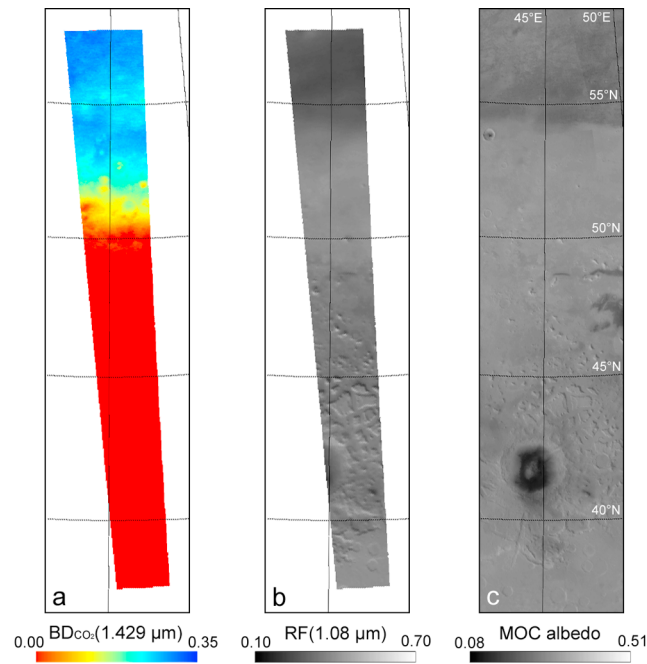
**Figure 8.** Same as Figure 4 but for (a)  $L_s$   $48.8^\circ$ – $51.9^\circ$ , (b)  $L_s$   $52.0^\circ$ – $58.6^\circ$ , (c)  $L_s$   $59.0^\circ$ – $61.5^\circ$ , (d)  $L_s$   $62.5^\circ$ – $66.7^\circ$ .





**Figure 9.** Same as Figure 4 but for (a)  $L_s$  66.8°–71.2°, (b)  $L_s$  73.6°–80.6°, (c)  $L_s$  81.5°–89.8°, (d)  $L_s$  90.3°–95.0°.





**Figure 10.** (a) The  $1.429\ \mu\text{m}$   $\text{CO}_2$  ice band depth for OMEGA observation 2210<sub>7</sub> ( $L_s$  299.5°). (b) Reflectance factor (RF) at  $1.08\ \mu\text{m}$  for the same observation. (c) MOC albedo data acquired in summer [Caplinger and Malin, 2001]. No albedo contrast is observed at the transition between defrosted soil and soil covered by frost. The albedo transition observed in summer at  $\sim 54^\circ\text{N}$  is still observed in winter with a weaker contrast, suggesting that winter frost is partly transparent at  $1.08\ \mu\text{m}$ .

it appears that the seasonal deposits are remarkably axisymmetric and uniform from  $L_s$  350° to  $L_s$  50° (Figures 5c to 7d). Departures from this uniformity are the circumpolar dark dunes field (also called polar erg) surrounding the permanent north polar cap, and some frost-rimmed craters and bright crater streaks extending counterclockwise from the crater. Crater streaks were also observed by MOC on the same longitudinal range, i.e., 210°E–300°E [James and Cantor, 2001], a sector which is known to be very active meteorologically with baroclinic wave activity [Hollingsworth et al., 1995, 1996]. After  $L_s$  350°, there is no tendency of known albedo features from the mineral soil to show up beneath the surface frost, supporting the fact that the frost is optically thick in the visible. The only exception is the polar erg which has a cryptic behavior, i.e., temperature near the  $\text{CO}_2$  frost point and albedo almost as low as the underlying soil [Kieffer et al., 2000]. TES albedo measurements indicated that the polar erg albedo is slightly higher in spring than in summer, suggesting that the frost covering the polar erg is not completely transparent [Kieffer and Titus, 2001]. James and Cantor [2001] reported that the albedo of the deposits at a fixed  $L_s$  increased from the polar cap toward the outer edge. They correlated this trend with the gradual increase of albedo with insolation that was observed in Viking data [Paige, 1985]. We do not observe such a trend on OMEGA mosaics.

[24] The northern seasonal deposits are much less symmetric between  $L_s$  50° and 67° (Figures 8a–8d). The deposits exhibit a polygonal shape observed by MOC at  $L_s \sim 60^\circ$  [James and Cantor, 2001] and already observed during previous northern Martian springs by the Hubble Space Telescope [Cantor et al., 1998] and by the Mariner 9 probe [Soderblom et al., 1973]. However, the seemingly straight boundaries connected by sharp angles observed by HST are resolved into a more irregular shape by OMEGA and MOC. Between  $L_s$  62° and 67° (Figure 8d), the shape of the deposits is less polygonal but still irregular. After  $L_s$  67° (Figure 9a), the geographic coverage of the OMEGA instrument is too small to enable a reliable analysis of the shape of the deposits.

[25] The albedo of the northern seasonal deposits increases during their retreat. This overall brightening as the Sun elevation increases was first noted by Paige [1985] and has also been observed during the 2000 and 2002 recessions by James and Cantor [2001]; Kieffer and Titus [2001]; Cantor et al. [1998]. Several processes have been proposed to explain this brightening: a decrease of the mean grain size combined with a decrease of the aerosols optical depth [Langevin et al., 2007], a process progressively removing the dust from the ice [Cantor et al., 1998] or a photometric behavior of the ices although this last phenomenon cannot fully explain the amplitude of albedo variation. This brightening is also observed for seasonal ices of the southern hemisphere and may be explained by self cleaning of the ice by solid-state greenhouse effect as discussed by Kieffer [2007] and Portyankina et al. [2010].

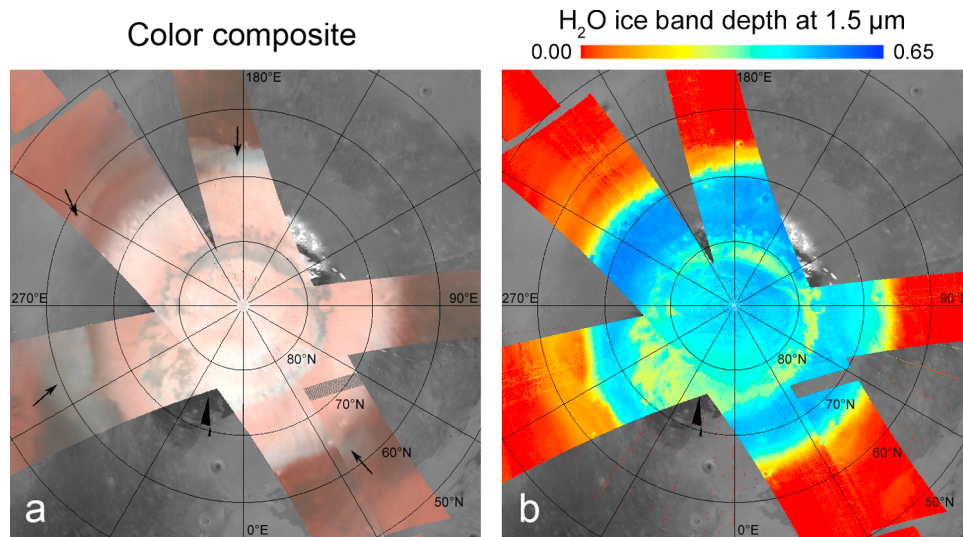
### 3.1.2. $\text{CO}_2$ Maps

[26] The monitoring of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  ices distributions provides a more detailed view of the deposits evolution. From  $L_s$  280° to 350°, only the edge of the seasonal deposits is monitored (Figures 4a to 5b). After  $L_s$  350°, we have access to a nearly full coverage of both ices distributions every degrees of  $L_s$ .

[27] The maximum extent of  $\text{CO}_2$  ice is  $49^\circ\text{N}$  at  $L_s$  289°.  $\text{CO}_2$  ice distribution is mostly axisymmetric at the beginning of the recession. It becomes less and less axisymmetric from  $L_s$  40° to  $L_s$  50°. After  $L_s$  50°, the distribution of  $\text{CO}_2$  ice is more and more patchy until its complete disappearance at  $L_s \sim 80^\circ$  (Figure 9c).

[28] The distribution of  $\text{CO}_2$  ice band depths is not as uniform as that of the albedo. Strong spatial variations are observed between  $L_s$  350° and 2.5° (Figures 5c and 5d). Linear structures observed near longitude 150°E at  $L_s$  350° (Figure 5c) correspond most likely to circumpolar clouds. A weaker signature of  $\text{CO}_2$  ice is observed on the circumpolar dark dunes field between  $L_s$  350° and  $L_s$  13° (Figures 5c to 6a). There is a general increase of  $\text{CO}_2$  ice band depth toward the north polar cap for a given  $L_s$ , from  $L_s$  10° to 40°. After  $L_s$  40°, this behavior is no longer observed.

[29] Between  $L_s \sim 40^\circ$  and  $L_s \sim 70^\circ$ , the  $\text{CO}_2$  ice signature unambiguously reappears at locations where it had previously disappeared. As an example, no  $\text{CO}_2$  ice is detected at  $L_s$  50° on a region located at 350°E/75°N (Figure 8a), while it is observed anew at  $L_s$  60° (Figure 8c). This surprising behavior requires a specific discussion which is beyond the scope of this article and will be discussed in detail in a specific article. Despite these nonuniformities, the general



**Figure 11.** Comparison between (a) a color composite mosaic from the OMEGA visible channel and (b) a H<sub>2</sub>O ice band depth mosaic, both acquired between  $L_s$  35.3° and 36.4°. Spectels at 699.7, 535.9, and 476.0 nm were used for the red, green, and blue layers, respectively, of the RGB composite. Arrows point to water ice clouds extending beyond the boundary of the receding northern seasonal deposits. These clouds are also observed on the H<sub>2</sub>O ice band depth mosaic, with band depths lower than 0.15 and a characteristically strong absorption at 3  $\mu$ m.

trend is a decrease of the CO<sub>2</sub> ice band depth throughout the retreat of the seasonal deposits.

### 3.1.3. H<sub>2</sub>O Maps

[30] The distribution of the H<sub>2</sub>O ice can be divided into two main categories. The first one is an area seemingly fitting with the seasonal deposits distribution in term of albedo (e.g., Figure 5c). H<sub>2</sub>O ice band depth over this area is greater than  $\sim 0.15$ . It will be called the high band depth area (HBDA) in the following. The second category is a wide area surrounding the first one with H<sub>2</sub>O ice band depth not exceeding 0.15, which we call low band depth area (LBDA).

[31] H<sub>2</sub>O ice band depth values are quite uniform over the HBDA, much more than CO<sub>2</sub> ice band depths. The polar erg departs from this uniformity with lower H<sub>2</sub>O ice signatures. The evolution of the H<sub>2</sub>O ice distribution in the HBDA is the same as the albedo distribution: it is axisymmetric from  $L_s$  280° to  $L_s$  50°, much less symmetric later on. H<sub>2</sub>O frost is mostly confined to the permanent north polar cap at  $L_s \sim 90^\circ$ . An increase of the H<sub>2</sub>O ice band depth is observed over the HBDA throughout the recession.

[32] The LBDA stretches far to the south, down to 30°N. It very likely corresponds to detection of water ice in clouds. North polar water ice clouds are prevalent near the edge of the seasonal deposits in the spring and late summer/early fall, forming the polar hood [e.g., Briggs and Leovy, 1974; James et al., 1994; Leovy et al., 1972; Christensen and Zurek, 1984]. Polar hood clouds generally appear at  $L_s$  160° [Wang and Ingersoll, 2002; Kieffer and Titus, 2001] and  $\sim 95\%$  of the surface between 60°N and 75°N is shrouded in a cloud cover by  $L_s$  185° [Wang and Ingersoll, 2002]. This polar hood persists during winter and retreats with the seasonal deposits during spring [Wang and Ingersoll, 2002], water ice clouds occurring within several degrees off the seasonal deposits edge [James and Cantor, 2001; Tamppari et al., 2008; Christensen and Zurek, 1984;

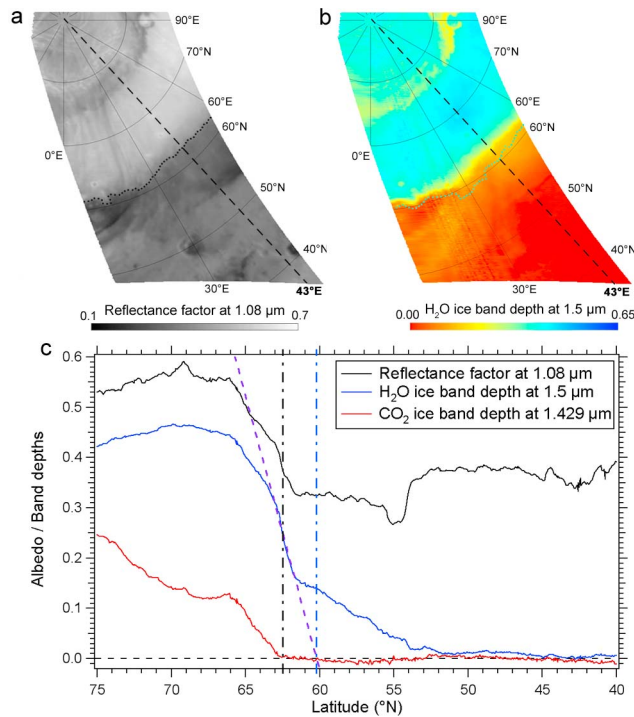
Cantor et al., 2010]. We made a color composite image from the OMEGA visible channel to highlight these water ice clouds at  $L_s$  35° (Figure 11). We chose the spectel at 699.7 nm for the red channel, at 535.9 nm for the green channel and at 476.0 nm for the blue channel. Scattering by water ice crystals is higher in the blue wavelengths than in the red ones, water ice clouds will thus appear bluish on a RGB mosaic [James, 1985; Cantor et al., 2001; Wang and Ingersoll, 2002]. Water ice clouds are pointed by arrows on Figure 11a. There is a clear correlation between their location and the spatial distribution of the LBDA. Another discrimination criterium is provided by the 3  $\mu$ m H<sub>2</sub>O ice absorption band shape. A visual inspection of spectra acquired in the LBDA shows that this band has a sharply rising edge between 3.4  $\mu$ m and 3.525  $\mu$ m, characteristic of micron-scale H<sub>2</sub>O ice particles in clouds [Langevin et al., 2007]. Most of the LBDA thus corresponds to water ice clouds rather than surface water frost, while it is not excluded that part of the 1.5  $\mu$ m absorption is due to surface frost on the north edge of the LBDA. This wide low band depths area is no more observed after  $L_s$  70° which is consistent with TES observation of the progressive north polar hood breakdown at  $L_s \sim 75^\circ$  [Tamppari et al., 2008].

## 3.2. Boundaries of the Deposits

[33] The boundaries of the deposits in term of albedo, CO<sub>2</sub> ice and H<sub>2</sub>O ice were retrieved from the OMEGA data set. They are compared to MOC and TES albedo boundaries and to TES and THEMIS infrared boundaries. Figures 12 and 13 illustrate the process followed to retrieve these boundaries. Figures 12 and 13 correspond to two different types of spatial evolution of the H<sub>2</sub>O ice band depth.

### 3.2.1. Albedo Boundary

[34] The MOC camera achieved the most complete set of observations of the northern seasonal deposits. The bound-



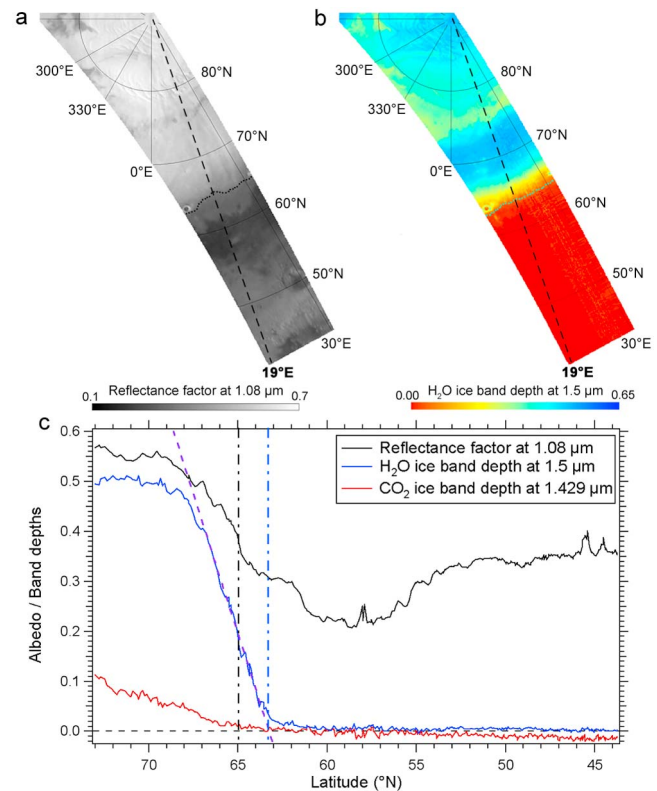
**Figure 12.** (a) Reflectance factor at 1.08  $\mu\text{m}$  for OMEGA observation 2742<sub>1</sub> ( $L_s$  18.7°). (b) The 1.5  $\mu\text{m}$  H<sub>2</sub>O ice band depth for the same observation. (c) Evolution of the reflectance factor at 1.08  $\mu\text{m}$  (black curve), 1.429  $\mu\text{m}$  CO<sub>2</sub> ice band depth (red curve) and 1.5  $\mu\text{m}$  H<sub>2</sub>O ice band depth (blue curve) as a function of latitude along longitude 43°E (black dashed line on Figures 12a and 12b) for this observation. The purple dashed line is the fit of the sharp decrease in the H<sub>2</sub>O ice band depth profile (see text). The dash-dotted black line at 62.5°N corresponds to the albedo boundary of the seasonal deposits while the dash-dotted blue line at 60.2°N corresponds to the H<sub>2</sub>O ice boundary. These boundaries are plotted as dotted curves on Figures 12a and 12b.

any of the seasonal ices was monitored thanks to their high albedo on MOC data. These boundaries were hand drawn for each mosaic, the deposits outer limit being located by visual inspection of the spatial albedo variation [Benson and James, 2005]. The same work was done on MARCI data covering spring 29 [Cantor et al., 2010]. We mostly used the same technique to retrieve the albedo boundary on OMEGA observations. Isoalbedo contours were drawn on each observation. The contour fitting the best the albedo edge of the deposits was chosen by visual inspection. For example, the albedo boundary is located at 43.0°E/62.5°N on Figure 12a and at 19.0°E/65.0°N on Figure 13a. As we can notice it does not correspond to the end of the albedo decrease on Figures 12c and 13c. Nevertheless, we used this method so as to make reliable comparisons with spring retreats monitored by MOC and MARCI. A low contrast between ices and defrosted soil can make the boundary more difficult to distinguish. In these situations, we used color composite mosaics from the OMEGA visible channel to enhance the contrast between frost and defrosted soil. As visible wavelengths are more sensitive to aerosol scattering than IR wavelengths, the presence of clouds along the edge

of the deposits can also cause confusion. We estimate the uncertainty on the albedo boundary latitude to be  $m$  0.5°.

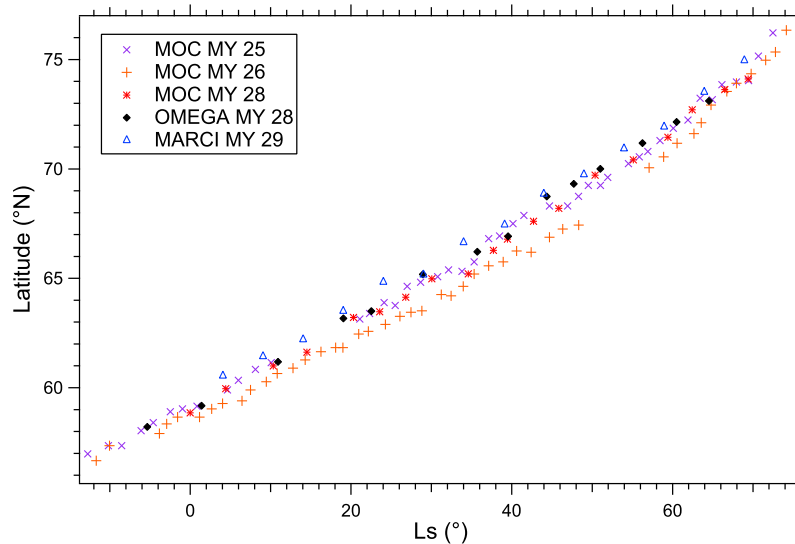
[35] No albedo boundary can be identified from  $L_s$  280° to  $L_s$  340° as the albedo of the seasonal deposits is then similar to that of outlying ice-free areas. The boundary is determined between  $L_s$  350° and  $L_s$  67°. After  $L_s$  67°, the spatial coverage of OMEGA is too small to retrieve a reliable boundary. OMEGA, MOC, and MARCI albedo boundaries were zonally averaged for each mosaic and plotted on the same graph (Figure 14). There is a very good agreement between MOC and OMEGA MY 28 albedo boundaries, slight discrepancies being within error bars. A general agreement is observed between the five boundaries, indicating that the retreat is very similar between different Martian years. A plateau in the north polar regression curve during early to midspring has been reported by ground-based observers [Capen and Capen, 1970; Iwasaki et al., 1979, 1982, 1999] and has been also observed by the Viking orbiters [James, 1979]. During this anomaly, the boundary of the seasonal deposits remains at a fixed latitude of about 65°N for several weeks before the retreat resumes. However, such a plateau is not observed on OMEGA, MOC and MARCI regression curves. The only major difference between these five boundaries is that the MOC boundary of MY 26 is shifted southward the other boundaries. This shift is up to 2°. Northern plains were thus covered by seasonal frost for a longer time during MY 26.

[36] The latitudinal evolution of this limit as a function of Martian days has been estimated. We obtain a mean recession speed of 0.11° of latitude (~6.2 km) per Martian day



**Figure 13.** Same as Figure 12 but for OMEGA observation 2879<sub>1</sub> ( $L_s$  36.4°).





**Figure 14.** Retreat of the northern seasonal deposits as observed by MOC during MY 25 (purple crosses), MY 26 (orange pluses) and MY 28 (red stars), by OMEGA during MY 28 (black diamonds) and by MARCI during MY 29 (blue triangles). The latitude of the zonally averaged albedo boundaries is plotted versus aerocentric solar longitude.

which is consistent with observations performed during previous Martian years [James and Cantor, 2001; Benson and James, 2005; Kieffer and Titus, 2001; Cantor et al., 2010].

### 3.2.2. CO<sub>2</sub> Boundary

[37] The formula giving the CO<sub>2</sub> ice band depth (see section 2.2.2) is adjusted so that the global average band depth value for regions surrounding the CO<sub>2</sub> deposits is equal to 0. But this zero level can fluctuate from one observation to another by  $\pm 0.02$ . In order to determine locally the latitude at which the CO<sub>2</sub> ice has disappeared, we evaluate the local mean value of the CO<sub>2</sub> ice band depth zero level for each observation. Then the boundary is defined as a threshold of 0.015 above this local mean zero level. For example, the CO<sub>2</sub> boundary is located at 43.0°E/63.0°N on Figure 12c and at 19°E/67.0°N on Figure 13c. We estimate the uncertainty on the CO<sub>2</sub> ice boundary to be  $\pm 0.3^\circ$  in latitude. No CO<sub>2</sub> ice boundary is drawn after  $L_s$  49° since the CO<sub>2</sub> ice distribution becomes patchy. The CO<sub>2</sub> ice boundary is plotted as a black line on CO<sub>2</sub> ice maps (Figures 4–7). It can be compared with the TES “crocus line” (see section 3.2.4).

### 3.2.3. H<sub>2</sub>O Boundary

[38] The latitudinal profile of H<sub>2</sub>O ice band depth on Figure 12c presents a two-step decrease. The first decrease is sharp, and the second is more gradual. These two decreases correspond to the two areas with H<sub>2</sub>O ice described in section 2.2.3. We clearly see these two regions on Figure 12b. The gradual decrease likely corresponds to absorption by water ice in clouds. Therefore the H<sub>2</sub>O frost boundary does not correspond to the end of the H<sub>2</sub>O ice band depth gradual decrease on Figure 12c. However, on Figure 13c, there is only a one-step almost linear sharp decrease. In that case, the H<sub>2</sub>O frost boundary corresponds to the end of the sharp decrease, at  $\sim 63^\circ$ N. We assume that the H<sub>2</sub>O ice band depth would decrease sharply and linearly until reaching the 0 level on Figure 12c if there was no absorption by water ice in clouds.

Therefore we fitted by a straight line the sharp decrease of the H<sub>2</sub>O ice band depth in both cases (purple line) and determined the intersection point between this line and the 0 band depth level. This technique works for a one-step sharp decrease and for a two-step decrease as well. On Figure 12, the H<sub>2</sub>O ice boundary is then located at 60.2°N. On Figure 13, it is located at 63.3°N. We estimate the error on the H<sub>2</sub>O ice boundary at  $\sim 0.5^\circ$  in latitude. No H<sub>2</sub>O ice boundary is drawn after  $L_s$  67° since the spatial coverage of OMEGA is too limited for a reliable analysis. The H<sub>2</sub>O ice boundary is plotted as a blue line on CO<sub>2</sub> ice maps (Figures 4–8).

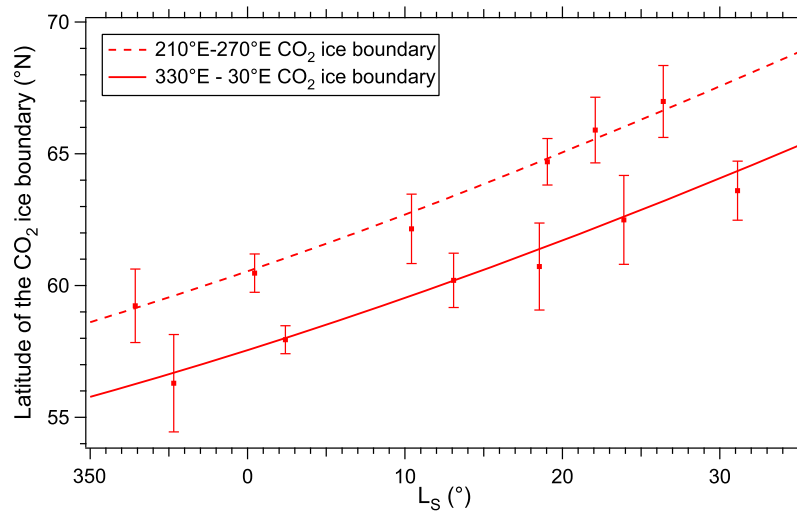
### 3.2.4. TES Crocus Line

[39] The last type of boundary we study is the TES crocus line. The crocus line is a thermal boundary corresponding to latitudes and longitudes where the 30  $\mu$ m brightness temperature rises above 165 K for a given  $L_s$  [Kieffer and Titus, 2001]. The threshold temperature is set slightly higher than the CO<sub>2</sub> ice temperature ( $\sim 150$  K) to account for the mix of surface temperatures that occurs in a latitude strip in spring [Kieffer and Titus, 2001]. TES was operating in a degraded mode at the end of the MGS mission, in 2006. Therefore bolometer temperatures were used instead of 30  $\mu$ m brightness temperatures to draw the MY 27–28 TES crocus line. Bolometer temperatures are more sensitive to the atmospheric temperature, resulting in a crocus line shifted northward the three previous crocus lines (T. Titus, personal communication, 2009). We decided to use the average of these three previous crocus lines, i.e., MYs 24–25, 25–26, and 26–27, instead of the MY 27–28 crocus line. The mean latitudinal difference for a given longitude and  $L_s$  between these three crocus lines is  $0.6^\circ$ . This mean crocus line is plotted on each mosaic as a dashed line. The  $L_s$  value for which it is plotted corresponds to the mean of each  $L_s$  interval.

### 3.2.5. Asymmetry of the Retreat

[40] Even though the seasonal deposits seem axisymmetric at the beginning of their retreat, some longitudinal variations





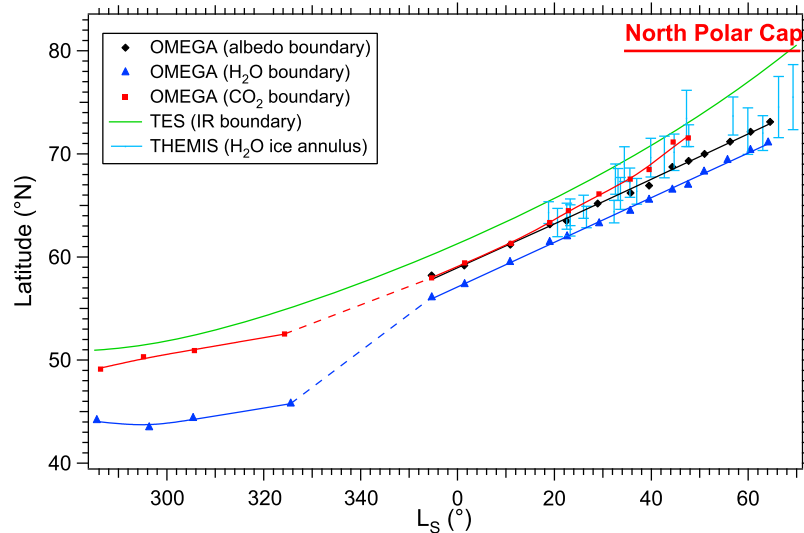
**Figure 15.** Spring evolution of the CO<sub>2</sub> ice boundary for longitudes 210°E to 270°E (dashed line) and 330°E to 30°E (solid line). The error bars refer to a latitude dispersion of  $\pm 2\sigma$  within each longitude range.

exist. The longitude segment 330°E–30°E is the slowest to regress, while the 210°E–270°E segment regresses the quickest, whatever the kind of boundary (albedo, CO<sub>2</sub> or H<sub>2</sub>O). This asymmetry is observed with MOC data during MY 24–25 and 25–26 for the same longitude segments [James and Cantor, 2001; Benson and James, 2005]. The CO<sub>2</sub> ice boundary recession curve is plotted for the longitude segments 330°E–30°E and 210°E–270°E in Figure 15. The temporal shift between the two curves is  $\sim 15^\circ L_s$ , which corresponds to  $\sim 32$  Martian days. The spatial shift is about  $3.2^\circ$  of latitude. A Mars Orbiter Laser Altimeter (MOLA) map of the north polar region shows that the 330°E–30°E segment corresponds to the lowest elevations of the circumpolar region, while the 210°E–270°E is slightly above average in elevation [Zuber *et al.*, 1998]. The higher pressure in the lower regions entails a higher radiative equilibrium temperature for the CO<sub>2</sub> ice [Fray and Schmitt, 2009], and thus a higher emitted thermal flux. It is compensated during winter by a higher condensation flux. Therefore the asymmetry observed is consistent with an enhancement of CO<sub>2</sub> condensation in the lower regions and thus a larger initial CO<sub>2</sub> ice depth. The condensation in the 210°E–270°E segment could also be influenced by strong weather patterns, such as an enhancement of the energy advection by the active storm zone in this longitude range [Hollingsworth *et al.*, 1995]. But other parameters such as the albedo of the ice during its sublimation phase could also be involved in this asymmetry, as it has been observed for the southern seasonal deposits recession [Schmidt *et al.*, 2009]. A statistical analysis of the parameters involved in the thermal equilibrium controlling the condensation and sublimation of the ice needs to be performed to clearly understand the origin of this asymmetry.

### 3.2.6. Intercomparison Between the Boundaries

[41] All these limits are zonally averaged and plotted on the same graph (Figure 16). First we observe that the H<sub>2</sub>O ice boundary is systematically shifted south of the CO<sub>2</sub> ice boundary. It implies that a CO<sub>2</sub>-free water ice annulus

surrounds the receding CO<sub>2</sub>-rich deposits. This water ice annulus corresponds to the one detected by TES and THEMIS on the basis of temperature measurements [Kieffer and Titus, 2001; Wagstaff *et al.*, 2008]. We notice that this water ice annulus is very extended, down to  $43^\circ\text{N}$  and  $\sim 6^\circ$  wide, before the beginning of its recession at  $L_s$  330°. This wide winter H<sub>2</sub>O ice annulus likely corresponds to the thin water ice frost observed to vary daily by the Viking Lander 2 at  $48^\circ\text{N}$  in Utopia Planitia [Jones *et al.*, 1979; Hart and Jakosky, 1986; Svitek and Murray, 1990], i.e., condensation of water ice during the night and partial sublimation during the day. After  $L_s$  350°, the water ice annulus is only  $2.0 \pm 0.8^\circ$  wide. Then the CO<sub>2</sub> ice boundary gradually recedes between  $L_s$  20° and 50° thus widening the annulus to  $\sim 4.6^\circ$  by  $L_s$  50°. After this date, it is hard to define an annulus since the CO<sub>2</sub> ice distribution becomes patchy but at that time CO<sub>2</sub>-free H<sub>2</sub>O ice areas begin to appear at all latitudes. The extension of the water ice annulus determined by OMEGA is thus clearly smaller than the  $\sim 5^\circ$  extension measured by TES during the MY 24–25 recession [Kieffer and Titus, 2001]. Wagstaff *et al.* [2008] report on the location and extent of the water ice annulus on the basis of THEMIS temperature measurements. These observations are plotted as light blue vertical bars on Figure 16. The extension and location of the water ice annulus detected by THEMIS are in good agreement with OMEGA observations between  $L_s$  20° and 40° except for occasional THEMIS detections shifted north compared to OMEGA detections at  $L_s \sim 35^\circ$ . Then, between  $L_s$  40° and 50°, THEMIS detections are systematically shifted more than  $2^\circ$  north OMEGA detections but the annulus extension still agrees. Discrepancies on the annulus location may come from the inhomogeneous coverage of THEMIS: THEMIS values correspond to observations made at specific longitudes while OMEGA boundaries are averaged over all longitudes. After  $L_s$  60°, the southern boundary of the THEMIS water ice annulus corresponds to the OMEGA H<sub>2</sub>O ice boundary. The evolution of the water ice annulus extent is therefore mostly similar on OMEGA and



**Figure 16.** Winter and spring evolution of the albedo (black diamonds), H<sub>2</sub>O ice (blue triangles) and CO<sub>2</sub> ice boundaries (red squares) observed by OMEGA are compared to TES crocus line (green curve) and water ice annulus extent observed by THEMIS (light blue curve). All limits have been zonally averaged. No CO<sub>2</sub> ice limit is plotted after  $L_s \sim 50^\circ$  since the CO<sub>2</sub> ice band depth distribution is too patchy to define a reliable CO<sub>2</sub> boundary. CO<sub>2</sub> and H<sub>2</sub>O ice boundary evolution is plotted with dashed lines between  $L_s$  325° and 355° because of the lack of data for this range of  $L_s$ . The averaged latitude of the north polar cap boundary is 80°N (horizontal red line).

THEMIS observations, but the annulus location diverges between the two instruments, maybe due to differences in spatial coverage.

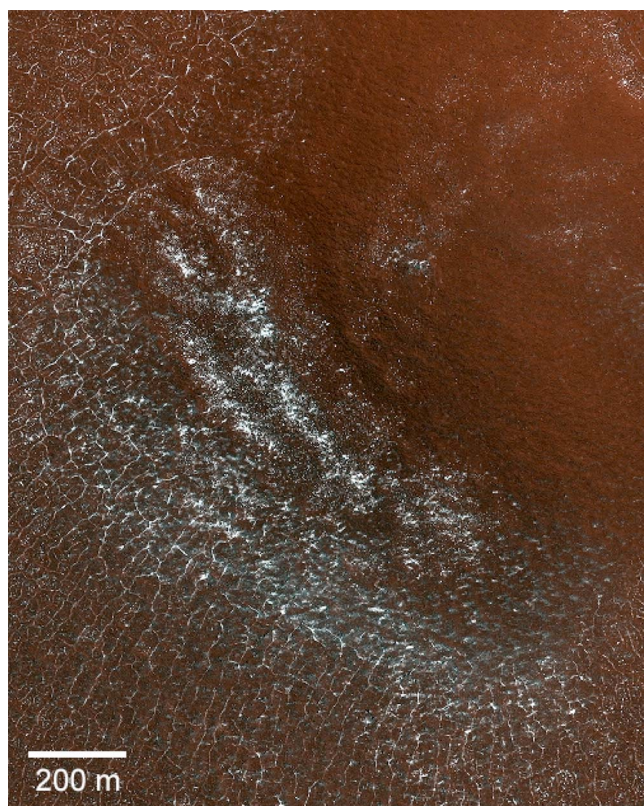
[42] One can also notice that the albedo limit of the seasonal deposits does not correspond to their outer limit, i.e., the water ice limit. A shift of  $\sim 2^\circ$  of latitude is observed between these two limits. However, we see on Figure 13c that albedo and H<sub>2</sub>O ice band depth stop decreasing at about the same latitude,  $\sim 63^\circ$ N. The origin of this shift is thus just due to the different methods used for determining the albedo “limit” (about midway of the decrease of the albedo contrast between ices and defrosted soil, determined by visual inspection) and the water ice limit (total disappearance of the ice signature). The “albedo boundary” given by this method tends to be located slightly northern than the true end of the albedo decrease. Water ice detected by OMEGA south of the visually located albedo limit has a lack of visual contrast with the bare defrosted soil and thus cannot be detected in the visible range, at least at the OMEGA spatial resolution. This water ice is probably dusty and spatially segregated at subpixel scale with already defrosted soil. Such a patchy configuration has already been observed by MOC [see *Malin and Edgett*, 2001, Figure 44b] and by the HiRISE camera onboard MRO, at a higher spatial resolution (Figure 17).

[43] Albedo and CO<sub>2</sub> ice boundaries of the seasonal deposits are first similar but after  $L_s$  20°, the CO<sub>2</sub> ice boundary regularly shifts north of the albedo boundary. It implies that the water ice annulus is only made of dusty water ice spatially segregated with defrosted soil before  $L_s$  20°. Then the annulus is made of both a constant  $\sim 2^\circ$  wide southern dusty and patchy water ice area and a northern brighter area with an extension which gradually increases to  $\sim 2^\circ$  at  $L_s$  50°.

[44] One can also observe that our CO<sub>2</sub> ice boundary is systematically shifted  $\sim 2^\circ$  south of the TES crocus line. However, these two boundaries do not correspond to the same spatial amount of CO<sub>2</sub> ice covering the surface. The surface temperature threshold for the TES crocus line is set to 165 K, i.e., 15 K above the CO<sub>2</sub> ice temperature, to account for the spatial mix of surface temperatures occurring during spring. A quick calculation indicates this surface temperature is obtained with a surface covered by 81% of CO<sub>2</sub> ice at 150 K and only 19% of H<sub>2</sub>O ice at 205 K. We set the CO<sub>2</sub> ice temperature to 150 K since it is its equilibrium temperature at 9 mbar [*Fray and Schmitt*, 2009], the mean surface pressure measured by Viking Lander 2 between  $L_s$  0° and 70° [*Hess et al.*, 1980]. The same temperature was measured by TES over the CO<sub>2</sub>-rich ice during MY 24–25 northern winter and spring [*Kieffer and Titus*, 2001]. The H<sub>2</sub>O ice temperature is set to 205 K since it is its equilibrium temperature at 9 mbar [*Fray and Schmitt*, 2009], assuming a water vapor mixing ratio in the low atmosphere of 0.03% [*Owen*, 1982]. The TES crocus line does not correspond to the disappearance of CO<sub>2</sub> ice on the surface but to the rise of surface temperature due to segregation between CO<sub>2</sub> and H<sub>2</sub>O ices. The OMEGA CO<sub>2</sub> ice boundary is defined as the end of this segregation with almost total disappearance of CO<sub>2</sub> ice on the surface.

### 3.3. Evolution of the Seasonal Deposits Stratigraphy

[45] An important issue is the growth of the bright northern part of the water ice annulus after  $L_s$  20°. Visual inspection of the CO<sub>2</sub> maps indicates that this phenomenon is correlated with a faster decrease of the area covered by the CO<sub>2</sub> ice signature leading to its patchy distribution by  $L_s$  50°. In particular, many disappearances of the CO<sub>2</sub> ice signature are observed in regions located north the TES crocus line,



**Figure 17.** Segregation between frost and defrosted soil observed by the HiRISE camera (PSP\_007642\_2480, 67.8°N, 234.0°E,  $L_s = 44.7^\circ$ ).

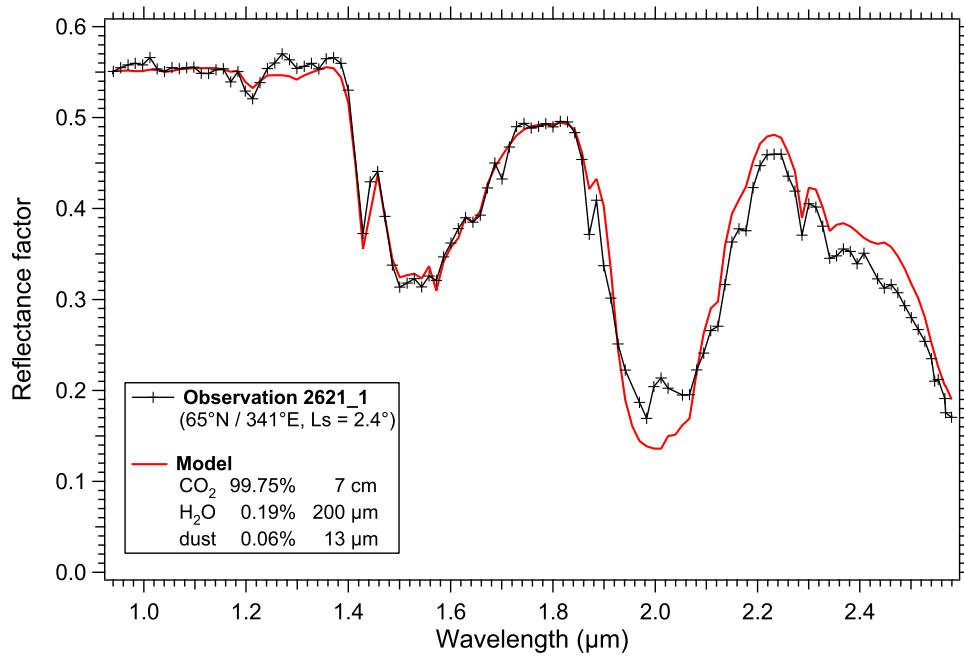
such as Olympia Planitia and the top of Gemina Lingula (see Figure 8b). Surface temperature therefore indicates the presence of abundant CO<sub>2</sub> ice in these regions but its spectral signature is absent. We thus conclude that CO<sub>2</sub> ice is overlaid by an optically thick cover, either of dust or of water ice, the two minor components included in CO<sub>2</sub>-rich ice.

[46] Adding an optically thick layer of dust on CO<sub>2</sub>-rich ice would strongly decrease the observed albedo, which is not the case as it remains the same or even increases south of the CO<sub>2</sub> ice boundary. A water ice frost layer overlying CO<sub>2</sub> ice is consistent with the observations of both high albedos and H<sub>2</sub>O ice signatures in regions where the CO<sub>2</sub> ice signature disappears. The following scenario can be proposed for the formation of this optically thick water frost layer: at the beginning of northern spring, a thick layer of CO<sub>2</sub> ice contaminated by H<sub>2</sub>O ice and dust particles covers the northern regions. We extracted a typical spectrum of this ice and modeled it so as to estimate the proportion of each component and its grain size (Figure 18). The OMEGA spectrum is extracted at 65.3°N/341°E from observation 2621<sub>1</sub> acquired at  $L_s = 2.4^\circ$ . It has been corrected for atmospheric absorption by a radiative transfer code developed by Douté [2009]. No aerosol correction has been made so the reflectance factor in the continuum and CO<sub>2</sub> and H<sub>2</sub>O ices band depths may be reduced by 10 to 30% from their expected value for a “clear atmosphere” [Vincendon et al., 2007]. Using a radiative transfer model in layered media [Douté and Schmitt, 1998] and optical constants of CO<sub>2</sub> and

H<sub>2</sub>O ices [Quirico and Schmitt, 1997; Grundy and Schmitt, 1998; Schmitt et al., 1998], we model this spectrum by an intimate mixture of 7 cm CO<sub>2</sub> ice grains contaminated by 0.19 wt % of 200  $\mu$ m H<sub>2</sub>O ice grains and 0.06 wt % of 13  $\mu$ m dust particles with uncertainties of the order of 20% coming from the lack of aerosol correction. The model fits well for the 1–2.5  $\mu$ m spectral range while strong discrepancies are observed for wavelengths greater than 2.5  $\mu$ m. It may be due to the early presence of a very thin layer of H<sub>2</sub>O ice above the CO<sub>2</sub>-rich ice. The exact composition of this water ice layer is beyond the scope of this paper and will be determined elsewhere. The aim here was to estimate the bulk composition of the CO<sub>2</sub>-rich deposit. Soon after spring sunrise, the incident solar flux is large enough to sublimate CO<sub>2</sub> ice but not the H<sub>2</sub>O ice grains trapped in it. A fine grained H<sub>2</sub>O ice layer gradually forms by segregation of the ice grains embedded in the CO<sub>2</sub> ice and it is left at the surface as the CO<sub>2</sub> ice sublimates. This layer of H<sub>2</sub>O grains progressively builds up and it eventually becomes optically thick, hiding the spectral signature of the underlying CO<sub>2</sub>-rich ice. Radiative transfer modeling shows that a 200  $\mu$ m thick layer of H<sub>2</sub>O ice is sufficient to completely hide the CO<sub>2</sub> ice band at 1.43  $\mu$ m (Figure 19). We modeled the CO<sub>2</sub>-rich ice by the intimate mixture we previously determined (see Figure 18) and the layer of H<sub>2</sub>O ice above this CO<sub>2</sub>-rich ice by 200  $\mu$ m H<sub>2</sub>O ice grains. We found that a H<sub>2</sub>O layer with a thickness similar to the grain size is already able to completely hide the 1.43  $\mu$ m CO<sub>2</sub> ice band as well as the other CO<sub>2</sub> ice bands between 1 and 4  $\mu$ m.

[47] Cull et al. [2010] analyzed Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) spectra acquired during spring over the Phoenix landing site and observed the early disappearance of the CO<sub>2</sub> ice spectral signature. They propose an alternative interpretation for this early disappearance: as CO<sub>2</sub> ice sublimates, it disintegrates into smaller grains which reduces its spectral signature. They model CRISM spectra by a layer of soil overlaid by an intimate mixture of CO<sub>2</sub> ice, H<sub>2</sub>O ice and dust of decreasing thickness, amount and grain size of CO<sub>2</sub> ice. An analysis of their modelizations led us to conclude that their interpretation is not correct. First of all, their modelizations do not fit correctly CRISM spectra at wavelengths where CO<sub>2</sub> ice absorbs. The CO<sub>2</sub> ice signature decreases in CRISM spectra and is no more observed by  $L_s 20^\circ$  while modelizations of Cull et al. [2010] clearly show the 1.43  $\mu$ m CO<sub>2</sub> ice absorption band at  $L_s 20^\circ$  and  $26^\circ$  with no obvious band depth decrease [see Cull et al., 2010, Figure 7]. Furthermore, for large grain sizes decreasing the grain size of CO<sub>2</sub> ice while keeping its amount constant in an intimate mixture results in an increase of the continuum reflectance and thus in an increase rather than a decrease of the 1.43  $\mu$ m CO<sub>2</sub> ice band depth. This situation is illustrated by radiative transfer modeling we made in an ice layer of the same composition than that of Cull et al. [2010] (see Figure 21). We also modeled the decrease of the CO<sub>2</sub>-rich layer thickness while keeping constant the amount of CO<sub>2</sub> ice and its grain size. It results in a decrease of the reflectance factor in the continuum but not in the medium to strong absorption bands; the CO<sub>2</sub> ice band depth (relative to continuum) therefore decreases but does not disappear. By decreasing the CO<sub>2</sub> ice amount with a constant grain size and layer thickness and increasing correspondingly the amount of H<sub>2</sub>O ice, the CO<sub>2</sub> ice signature

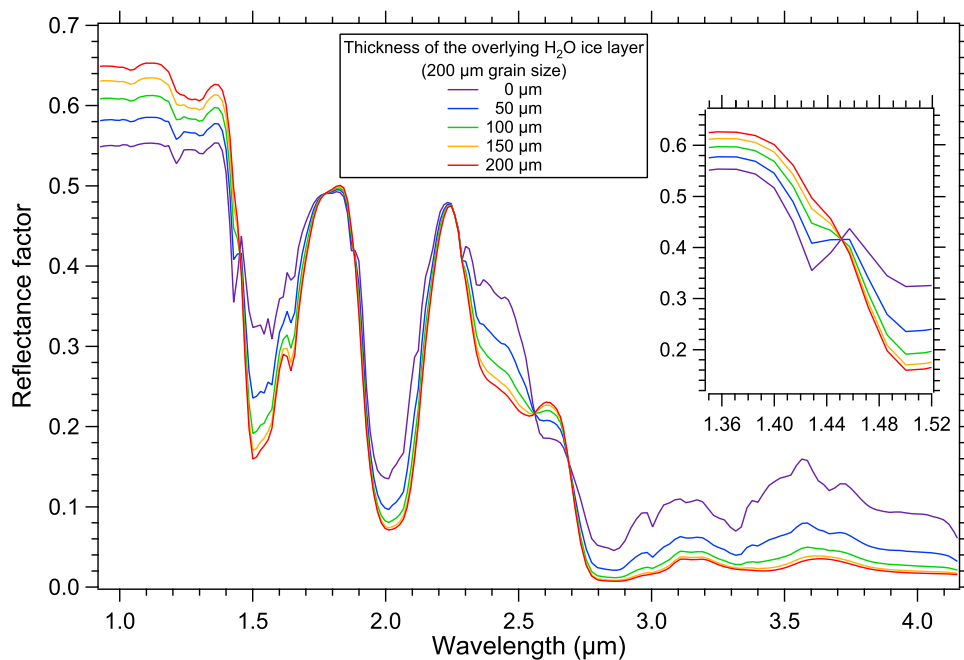




**Figure 18.** Modeling of a typical spectrum of the CO<sub>2</sub>-rich ice deposits in the early stage of the retreat ( $L_s = 2.4^\circ$ ). Black line with crosses is observed spectrum of seasonal deposits. Red line is modeled spectrum assuming a granular mixture of CO<sub>2</sub> ice with inclusions of H<sub>2</sub>O ice and dust. Components percentages are weight percentages.

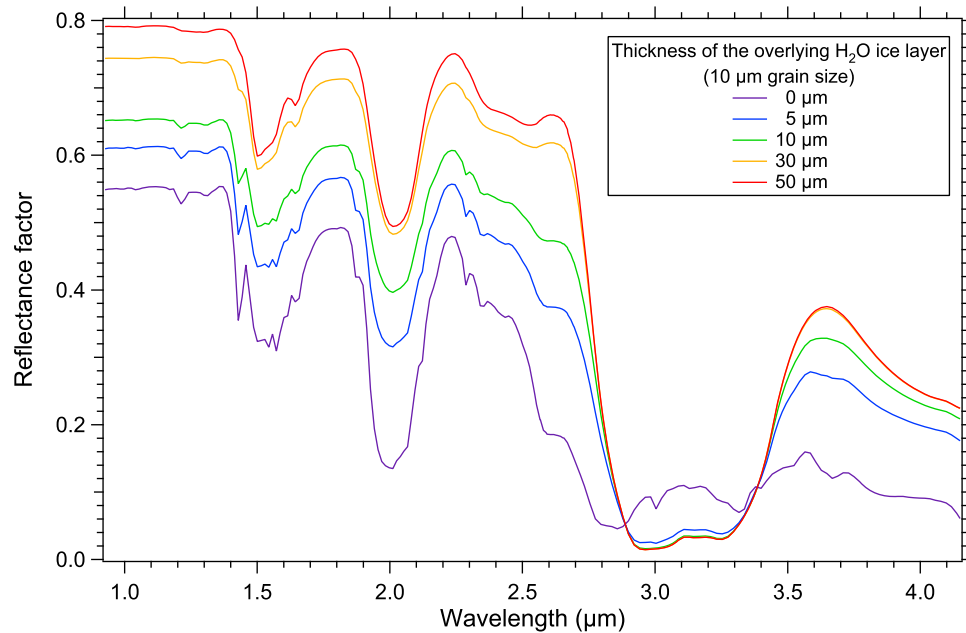
also decreases without disappearing and H<sub>2</sub>O ice absorption increases. Therefore a simple evolution of CO<sub>2</sub> ice amount and/or grain size in the layer is not enough to explain the early disappearance of the CO<sub>2</sub> ice signature. It requires the build up of an optically thick layer of H<sub>2</sub>O ice.

[48] This scenario of evolution also explains the increase of the water ice annulus extent after  $L_s 20^\circ$ . It is known from GRS and MOLA observations that the thickness of the seasonal deposits increases from the outer condensation limit at  $\sim 50^\circ\text{N}$  to the pole where the thickness is of the order of



**Figure 19.** Modeled spectra of CO<sub>2</sub> ice containing H<sub>2</sub>O ice and dust particles and overlaid by a layer of 200  $\mu\text{m}$  grain size H<sub>2</sub>O ice with various thickness. Notice that a H<sub>2</sub>O ice layer with a thickness lower than the H<sub>2</sub>O ice grain size corresponds to a partial coverage of the CO<sub>2</sub>-rich ice by H<sub>2</sub>O ice.





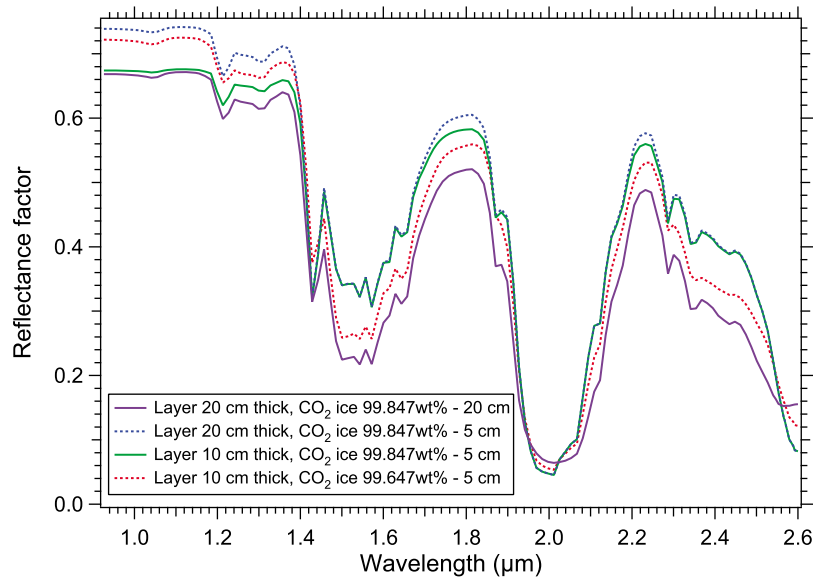
**Figure 20.** Modeled spectra of CO<sub>2</sub> ice containing H<sub>2</sub>O ice and dust particles and overlaid by a layer of 10  $\mu\text{m}$  grain size H<sub>2</sub>O ice with various thickness.

1 m [Smith *et al.*, 2001; Mitrofanov *et al.*, 2003; Aharonson *et al.*, 2004]. If we assume that the fractional abundance of H<sub>2</sub>O ice in the seasonal deposits before their retreat is mostly constant with latitude, then a column of seasonal deposits located at higher latitude will contain more H<sub>2</sub>O ice. Therefore, the total amount of H<sub>2</sub>O ice grains released at the surface by the sublimation of CO<sub>2</sub>-rich ice along the border of the CO<sub>2</sub> deposits increases with latitude, and thus  $L_s$ . The southernmost sublimating CO<sub>2</sub>-rich deposits will thus be progressively hidden by an overlying layer of released H<sub>2</sub>O ice grains, with increasing thickness with latitude. This surficial optically thick layer leads to an apparent increase of the water ice extent at higher latitudes. The growing northern part of this water ice annulus has a higher albedo since it consists of sublimating CO<sub>2</sub>-rich ice overlaid by optically thick H<sub>2</sub>O ice instead of H<sub>2</sub>O ice spatially segregated with defrosted soil for the southern regions.

[49] Cold trapping of water vapor coming from the sublimating part of the water ice annulus may also explain the growing of its bright northern part and the early disappearance of the CO<sub>2</sub> ice signature at higher latitudes. The amount of water ice contained in the water ice annulus should increase with latitude, or  $L_s$ , since it is composed of water ice from the CO<sub>2</sub>-rich ice added to the early H<sub>2</sub>O frost deposited over the soil during fall, with thickness probably also increasing with latitude. Thus an increasing amount, and flux, of water vapor is released to the atmosphere by the sublimation of the water ice annulus. Due to baroclinic wave activity at the edge of the deposits, part of this water vapor can diffuse northward over the CO<sub>2</sub>-rich ice and be either cold trapped directly at the surface of the CO<sub>2</sub>-rich ice or condense in the cold near-surface atmospheric layer and settle on the surface, as suggested by Houben *et al.* [1997]. The exact size of H<sub>2</sub>O ice grains condensed by cold trapping of water vapor on CO<sub>2</sub>-rich ice is not known. The mechanism of cold trapping of water vapor is invoked

by Bass *et al.* [2000] to explain the late summer brightening of the north permanent cap. This brightening is well reproduced by an ice deposit 10 to 50  $\mu\text{m}$  thick. Furthermore, it is consistent with the Hart and Jakosky [1986] estimates of approximately 10  $\mu\text{m}$  of ice deposited at the Viking Lander 2 site. Therefore we consider that water vapor should condense on CO<sub>2</sub>-rich ice in the form of H<sub>2</sub>O ice grains about, or less than, 10  $\mu\text{m}$  in size. Radiative transfer modeling shows that a 60  $\mu\text{m}$  thick layer of 10  $\mu\text{m}$  grain H<sub>2</sub>O ice is sufficient to completely hide the CO<sub>2</sub> ice band at 1.43  $\mu\text{m}$  (Figure 20). The building of a water ice layer made of 10  $\mu\text{m}$  grains results in a large increase of the albedo but a stable H<sub>2</sub>O ice band depth. Successive increases of albedo (+50–60%) and then of H<sub>2</sub>O ice band depth (+20–30%) are observed at locations where the CO<sub>2</sub> ice signature disappears. Therefore the layer of water ice hiding the CO<sub>2</sub> ice signature should be made of a mix of H<sub>2</sub>O ice grains coming from the two sources: H<sub>2</sub>O grains inside the CO<sub>2</sub> seasonal ice layer and water vapor trapped at its surface. The analysis of the exact composition and texture of this overlying water ice layer and of its temporal evolution, not in the scope of this paper, should give us clues on its origin(s) and evolution process(es) and will thus constrain the mobility of water vapor coming from the sublimating part of the water ice annulus and from subsequent desorption of soil minerals [Beck *et al.*, 2010] (Figure 21).

[50] We previously reported on the overall brightening of the northern seasonal deposits during their retreat (see section 3.1.1). Many mechanisms have been invoked to explain this brightening. The gradual building of an optically thick layer of H<sub>2</sub>O ice over CO<sub>2</sub>-rich ice certainly contributes to this brightening since radiative transfer modeling shows that this configuration leads to an increase of the albedo of typically 20–50% depending on the upper layer H<sub>2</sub>O grain sizes (Figures 19 and 20).



**Figure 21.** Modeled spectra of a layer of soil overlaid by an intimate mixture of CO<sub>2</sub> ice, H<sub>2</sub>O ice and dust. Purple solid line is a 20 cm thick layer of 99.847 wt % CO<sub>2</sub> ice (20 cm grain size) + 0.15 wt % H<sub>2</sub>O ice (200 μm grain size) + 0.003 wt % dust (13 μm grain size) overlying a layer of soil (30 μm grain size). Blue dashed line is same thickness and composition but with 5 cm CO<sub>2</sub> ice grains. Green solid line is same composition and grain size but the layer is 10 cm thick. Red dashed line is a 10 cm thick layer of 99.647 wt % CO<sub>2</sub> ice (5 cm grain size) + 0.35 wt % H<sub>2</sub>O ice (200 μm grain size) + 0.003 wt % dust (13 μm grain size) overlying a layer of soil (30 μm grain size).

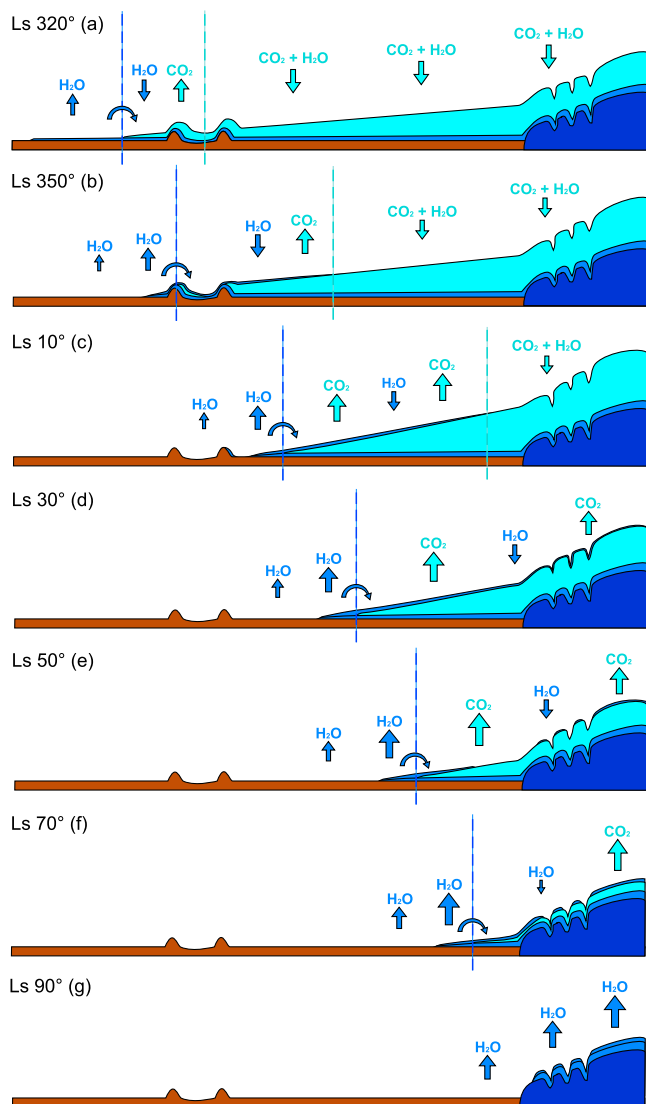
[51] Between  $L_s \sim 50^\circ$  and  $70^\circ$ , the CO<sub>2</sub> ice signature strongly reappears in locations where it had previously disappeared. This behavior occurs mostly on the circum-polar dark dunes field and in spiral troughs over the north permanent cap (Figure 8c and 8d). We also observe strong increases of the CO<sub>2</sub> ice signature in locations where it had not completely disappeared. Since we observe the modification of the CO<sub>2</sub> ice band depth by comparing two successive maps with a time lag of less than  $4^\circ$  of  $L_s$ , these late increases are very sharp. In the following, the late increases of the CO<sub>2</sub> ice signature are called LICs events. We have demonstrated that the formation of a H<sub>2</sub>O ice layer over the sublimating CO<sub>2</sub>-rich ice is responsible for the early disappearance of the CO<sub>2</sub> ice signature. Thus LICs events may be due to either the removal of this H<sub>2</sub>O ice layer or to condensation of CO<sub>2</sub> ice over this water ice layer. Erosion by katabatic winds over the northern cap and venting processes over the dark dune erg are most likely responsible for the disruption of the overlying H<sub>2</sub>O ice layer and/or recondensation of CO<sub>2</sub> ice which leads to LICs events. These mechanisms require a specific discussion which is beyond the scope of this article and will be discussed in detail in a future article.

[52] Early disappearances of the CO<sub>2</sub> ice signature are not systematically followed by LICs events. For example, we observe the disappearance of the CO<sub>2</sub> ice signature at  $L_s \sim 60^\circ$  on top of Gemina Lingula but no increase of the CO<sub>2</sub> ice signature later. In this location, the CO<sub>2</sub> ice remains hidden below the upper millimeters thick water ice layer until its complete sublimation. To summarize, the gradual building of a water ice layer overlying the CO<sub>2</sub>-rich deposits after  $L_s \sim 20^\circ$  is the general behavior observed on the northern seasonal deposits. It results in the early disappearance of the

CO<sub>2</sub> ice signature on many locations, followed locally by the late increase of the CO<sub>2</sub> ice signature. LICs events are also observed in locations where the overlying water ice layer was not thick enough to hide the CO<sub>2</sub> ice signature.

#### 4. Discussion and Conclusion

[53] From the spatial and temporal evolution of albedo and ice band depths, we propose a scenario that describes the late winter and spring evolution of the northern seasonal deposits (Figure 22). Figure 22a corresponds to the state of the seasonal deposits soon after the beginning of the recession, at  $L_s \sim 320^\circ$ . They are composed of two layers: a bottom layer of H<sub>2</sub>O ice and an overlying layer of CO<sub>2</sub> ice contaminated by H<sub>2</sub>O ice and dust. This layering is the result of the condensation stages that occurred during late autumn and winter. First the condensation of water frost starts during the night with water frost sublimating completely during the day. The latitude-time dependence of the first frosts will depend on the partial water vapor pressure in the atmosphere. In a second step, when the sun is low enough, the frost persists all day long [Jones *et al.*, 1979]. At this stage the accumulation rate should increase due to the positive feedback of the surface albedo on the thermal balance. This frost may also partly diffuse into the upper layer of soil and be adsorbed on mineral grains [Beck *et al.*, 2010] or possibly form some ice-cemented crust. Vapor diffusion and condensation at some depth will occur if there is a negative thermal gradient at some time of the daily cycle. In a second stage, when the thermal balance allows the surface temperature to drop below the CO<sub>2</sub> freezing point, CO<sub>2</sub> frost can start to condense including tiny amounts of water ice grains and



**Figure 22.** Possible sketch of the temporal evolution of the northern seasonal deposits. Latitudinal cross sections of the seasonal deposits show increasing  $L_s$  with vertical scale not respected for clarity. Dark blue is water ice in the north permanent cap (right). Medium blue is dusty water ice composing the underlying frost and the water ice annulus. Light blue is the  $\text{CO}_2$ -rich ice contaminated with dust and water ice. The dashed light blue line corresponds to the condensation/sublimation transition of  $\text{CO}_2$  ice while the dashed medium blue line corresponds to the condensation/sublimation transition of  $\text{H}_2\text{O}$  ice. For clarity, water ice clouds and hazes are not represented. They are present within several degrees off the seasonal deposits edge until  $L_s \sim 70^\circ$ . See text for complementary explanation.

dust particles (see Figure 18). This condensation should be first a diurnal condensation/sublimation cycle but at high latitudes, typically north of a latitude  $5^\circ$ – $10^\circ$  below the midday terminator, condensation will occur continuously at a rate mostly determined by the surface  $\text{CO}_2$  thermal emission and subsurface conduction [Forget *et al.*, 1999;

Lewis *et al.*, 1999]. At lower latitudes, where the daily average thermal balance is negative and net accumulation occurs, the condensation/sublimation diurnal cycle should still be effective. The thin water frost underneath should then be “frozen” at the  $\text{CO}_2$  ice temperature and water vapor diffusion inside the regolith is no longer efficient. The initial  $\text{H}_2\text{O}$  frost condensation and its associated surface albedo increase should help in lowering the surface temperature and thus may initiate  $\text{CO}_2$  condensation earlier, or at lower latitude, than without this precursor frost. The result should be a layer of  $\text{CO}_2$ -rich ice with a thickness gradient from the outer condensation limit at about  $50^\circ$  latitude to the pole, with a thickness of the order of 1 m [Smith *et al.*, 2001; Mitrofanov *et al.*, 2003; Aharonson *et al.*, 2004] on top of a millimeters thick layer of  $\text{H}_2\text{O}$  frost and of centimeters of icy soil. To what extent microphysical evolutions of these frosted soil,  $\text{H}_2\text{O}$  frost and  $\text{CO}_2$  ice layers may occur during these condensation stages is still an open question. A striking example is the observation of transparent frost in northern winter, at  $L_s$  329° (Figure 10). It suggests that  $\text{CO}_2$ -rich deposits could be initially in slab form. Based on physical models, seasonal  $\text{CO}_2$  deposits on Mars can undergo seasonal densification into a nonporous, polycrystalline layer, provided freshly condensed grains are sufficiently small ( $<10 \mu\text{m}$ ) [Eluszkiewicz, 1993].  $\text{CO}_2$  slab ice has been invoked to explain the observations of cold surfaces with low albedo in the so-called southern “cryptic” region [Kieffer *et al.*, 2000], interpreted either as translucent ice with partial dust contamination at the surface of the ice [Kieffer, 2007] or by extensive dust contamination close to the surface of a  $\text{CO}_2$  ice layer [Langevin *et al.*, 2006]. This configuration is also observed near the edge of the northern seasonal deposits in winter. However, we have shown that  $\text{CO}_2$ -rich ice is no longer transparent at  $L_s$  350°, so a change in the optical properties of the  $\text{CO}_2$  frost has occurred between  $L_s$  329° and  $L_s$  350°. As  $\text{CO}_2$  ice sublimates, the surface layer may disintegrate into smaller grains [Titus *et al.*, 2001] and lead to a nontranslucent  $\text{CO}_2$  ice with an albedo higher than defrosted soil, if the contamination of  $\text{CO}_2$  ice layer by dust is low enough, which is evidenced by spectral modeling (Figure 18). An alternative solution is that  $\text{CO}_2$  ice stays in slab form as it sublimates, but a layer of fine grained  $\text{H}_2\text{O}$  ice forms on top of the sublimating  $\text{CO}_2$  ice. As shown with spectral modeling (Figures 19 and 20), the formation of such a water frost layer results in a strong albedo increase. A more detailed spectral model is needed to specify which evolution scenario is actually occurring on Mars.

[54]  $\text{CO}_2$ -free water ice located on the left part of Figure 22a corresponds to daily water frost and initially extends about  $6^\circ$  latitude south of the observed edge of the  $\text{CO}_2$ -rich deposits. Progressive heating of the ice by the sun causes the  $\text{CO}_2$  ice sublimation. Sublimation flux decreases with increasing latitude and condensation of  $\text{CO}_2$  ice still occurs at high latitudes (Figure 22a). Transition between net condensation and sublimation of  $\text{CO}_2$  ice is illustrated by a dashed blue vertical line. Since the  $\text{H}_2\text{O}$  ice radiative equilibrium temperature is higher than that of  $\text{CO}_2$  ice,  $\text{H}_2\text{O}$  ice sublimation occurs at lower latitudes, unless partial water vapor pressure is above its saturation point, and condensation occurs over the cold  $\text{CO}_2$  ice. A dashed medium blue line



illustrates the transition between condensation and sublimation of H<sub>2</sub>O ice.

[55] Extension of ground covered by seasonal water frost decreases from  $L_s$  320° to 350° since less water frost condenses during the night than sublimates during the day (negative net daily condensation balance). It leads to a narrow water ice annulus about 2° of latitude wide (Figure 22b). It is composed of the initial icy soil and of two H<sub>2</sub>O ice layers: a bottom water frost layer condensed during late autumn and a top layer made of H<sub>2</sub>O ice released by the sublimation of the CO<sub>2</sub>-rich ice layer. H<sub>2</sub>O ice previously contained in CO<sub>2</sub>-rich ice also forms a thin layer overlying sublimating CO<sub>2</sub>-rich ice located at higher latitudes. Water vapor is released by the sublimation of the water ice annulus (right upward “H<sub>2</sub>O” arrow) and by water desorption and possibly dehydration from regolith minerals (left upward “H<sub>2</sub>O” arrow) [Pommerol *et al.*, 2009; Beck *et al.*, 2010]. Part of this water vapor may diffuse in the low atmosphere toward higher latitude and be cold trapped on the CO<sub>2</sub>-rich ice as suggested by Houben *et al.* [1997] and discussed by Bass and Paige [2000], and thus be added to the overlying water ice layer.

[56] Marked slope variations, as in craters, lead to spatial segregation between CO<sub>2</sub> ice and H<sub>2</sub>O ice (Figure 22b). CO<sub>2</sub> ice on south facing slopes sublimates quicker than CO<sub>2</sub> ice on north facing slopes. It leads to north facing slopes covered by CO<sub>2</sub>-rich ice and south facing slopes only covered by dusty H<sub>2</sub>O ice. After complete disappearance of CO<sub>2</sub> ice, sublimation of water ice leads to north facing slopes covered by dusty water ice and defrosted south facing slopes (Figure 22c). This kind of spatial segregation is expected to occur at various scales: regional with regional topography; medium scale associated with features such as with craters and dunes; and low spatial scales associated with features like polygonal terrains.

[57] CO<sub>2</sub> ice condensation no longer occurs after  $L_s$  30° (Figure 22d), and CO<sub>2</sub> ice sublimation flux increases with increasing solar flux. Accumulation of water ice previously contained in CO<sub>2</sub>-rich ice thickens the overlying water ice layer. It results in the progressive hiding of the CO<sub>2</sub> ice signature on the border of the seasonal deposits and the gradual increase of the water ice annulus extent. It is important to note that we define this water ice annulus as the contiguous region located south of the CO<sub>2</sub> ice signature boundary in which the H<sub>2</sub>O ice signature is spectrally detected. But regions located south of the CO<sub>2</sub> ice signature boundary may still be covered by CO<sub>2</sub> ice after  $L_s$  20° since CO<sub>2</sub> may be hidden by an overlying optically thick layer of water ice. After  $L_s$  20°, the water ice annulus is thus composed of a southern annulus made of a layer of dusty water ice and of a northern annulus with optically thick water ice overlying sublimating CO<sub>2</sub>-rich ice. Temperature measurements at high spatial resolution may help to determine the exact extent of CO<sub>2</sub>-rich ice on the ground. After  $L_s$  ~50°, the gradual build up of the water ice layer overlying sublimating CO<sub>2</sub>-rich ice results in the disappearance of the CO<sub>2</sub> ice signature at many locations at high latitudes up to the north pole, thus destroying the annulus structure of the area displaying only water ice signature and resulting in a patchy distribution of the CO<sub>2</sub> ice signature. Then the H<sub>2</sub>O ice overlying layer is disrupted locally (Figure 22e), and the CO<sub>2</sub> ice band depth suddenly increases. This late CO<sub>2</sub> ice signature increase preferentially

occurs on the circumpolar dark dunes field and in the numerous north permanent cap spiral troughs. It is observed until  $L_s$  70° (Figure 22f). The overlying water ice layer is likely removed by katabatic winds in the spiral troughs and by venting process on the polar erg where there is also probably condensation of CO<sub>2</sub> ice above. At places where none of these processes occur, such as on the cap plateaus, the CO<sub>2</sub> ice remains hidden below the upper millimeters thick water ice layer but continue to sublimate until exhaustion. After  $L_s$  70°, no new late increase of CO<sub>2</sub> ice signature occurs and the CO<sub>2</sub> ice band depth decreases at all places where the H<sub>2</sub>O layer has been removed, until complete disappearance of CO<sub>2</sub> ice at  $L_s$  80°.

[58] The final stage of the evolution of the seasonal deposits is the sublimation of the remaining dusty H<sub>2</sub>O ice layer made of three different water ice sources: H<sub>2</sub>O frost condensed on the ground during autumn, H<sub>2</sub>O ice grains included in the CO<sub>2</sub> ice layer during its winter condensation, and H<sub>2</sub>O vapor cold trapped over the CO<sub>2</sub> ice layer during the spring retreat. It corresponds to the large pulse of water vapor released in the atmosphere observed by Mars Atmospheric Water Detector (MAWD) and Infrared Thermal Mapper (IRTM) [Bass and Paige, 2000]. An open question is whether the annual water frost budget is positive or negative on the permanent north polar cap. If it is positive, water frost accumulates from year to year. On the contrary, a negative water frost budget means that the north permanent cap is losing mass from year to year.

[59] Northern seasonal deposits differ from the southern ones by the amount of H<sub>2</sub>O ice involved. In the south the low amount of water trapped in the CO<sub>2</sub> ice [Langevin *et al.*, 2007] precludes the formation of a water ice annulus and of an optically thick water ice layer on top of the CO<sub>2</sub> ice. This water ice plays a major role in the winter and spring evolution of the northern seasonal deposits. In particular the moving water ice annulus provides a strong source of atmospheric water vapor at low latitude and right from the end of northern winter. This localized and early vapor source above the water ice annulus is very probably underestimated or spatially diluted in most numerical general circulation models (GCMs). Very recent reanalysis of TES measurements of the spatial and temporal distribution of water vapor during three Martian years clearly shows “an annulus of water vapor growing above the edge of the retreating seasonal cap during spring” [Pankine *et al.*, 2010]. Such a narrow and strong water vapor annulus (up to more than two times the column abundance of water vapor just a few degrees latitude away from the annulus) is clearly not simulated by GCMs. One important question is where is exactly located this water vapor in the atmosphere. These observations are column densities and there may be much more contrast between near-surface partial vapor pressures above and away from the 2° wide ice annulus water source because the water vapor will not mix rapidly vertically. Strong temperature gradients also occur between the receding CO<sub>2</sub>-rich ice and the hotter dirty water ice annulus. This may favor strong near-surface poleward winds that will transport most of the vapor over the cold CO<sub>2</sub>-rich ice and thus provide an efficient mechanism of supply for the cold-trapped water layer of fine water ice grains that we propose to overlie the CO<sub>2</sub>-rich ice.

[60] What emerges from the OMEGA observations is a very dynamic behavior of water frost and water vapor, from subli-

mation of the water ice annulus and icy soil to recondensation of water vapor on top of the CO<sub>2</sub>-rich ice. A water molecule is possibly subjected to a series of such events during the whole seasonal ices retreat, and this near surface process coupled with the katabatic wind events may strongly contribute to accumulation of water ice on the permanent polar cap and, possibly, preferentially at some specific places. Water frost budget may be thus variable over the polar cap.

[61] This evolution scenario has to be tested by modeling temporal sets of spectra for characteristic regions. Spectral modeling will provide more quantitative information on the deposits and their evolutions: organization of the ices and dust components, grain sizes, fraction of ground covered by ices, mixing ratio, dust content and thickness of the water ice layers. It will thus help to understand the various micro-physical processes occurring during the deposition, condensation and sublimation stages of the seasonal ices. These processes should strongly constrain the spatial distribution and temporal evolution of fluxes of volatiles between the atmosphere and the surface, useful information for models of the Martian climate. Knowledge of the localization, volatility and mobility through the atmosphere of the various water sources may lead to improved Martian climatic models and improve our comprehension of the Martian water cycle.

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